Detection, Prevention and Remediation of Leaks from Underground Storage Tanks

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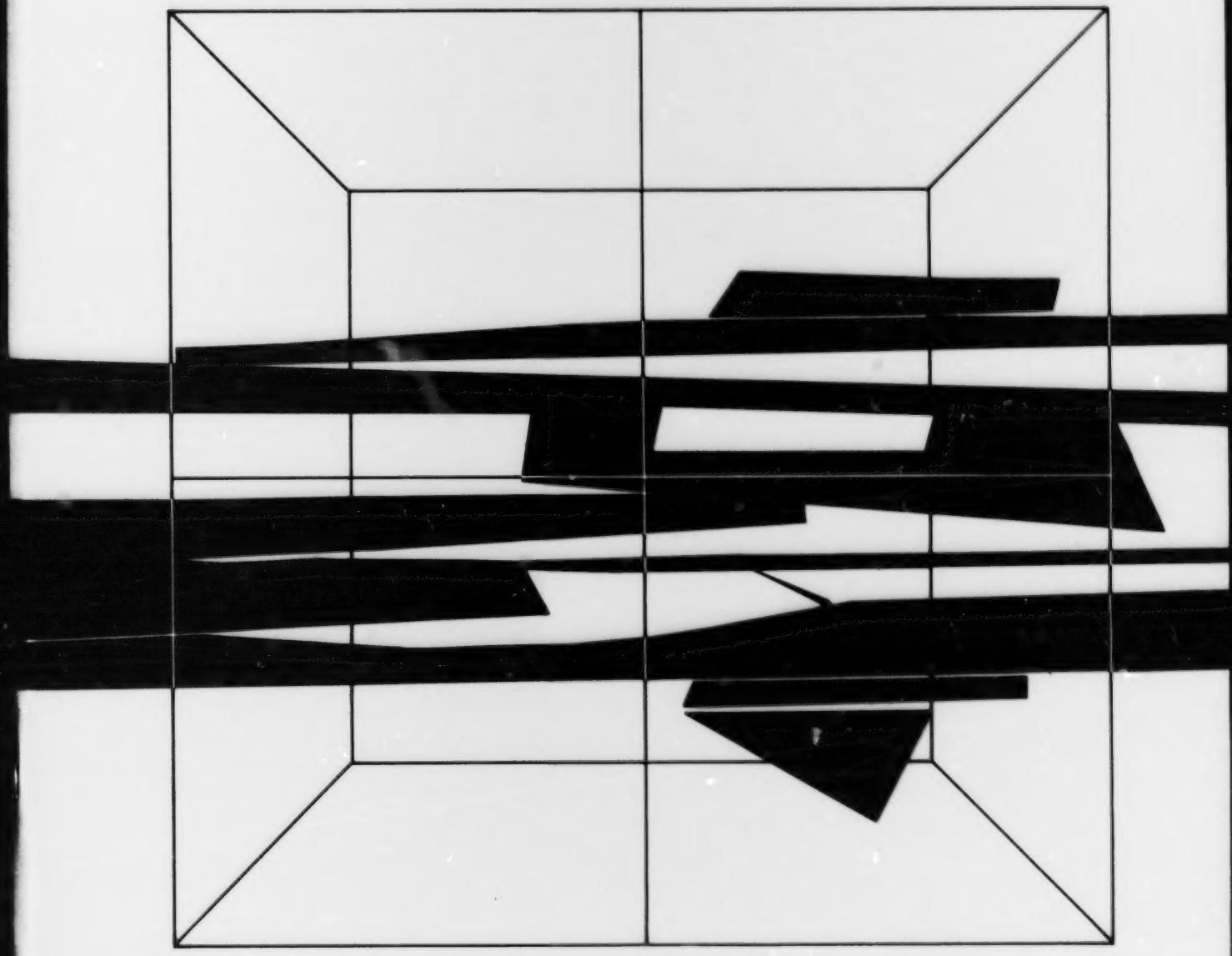
February 1989



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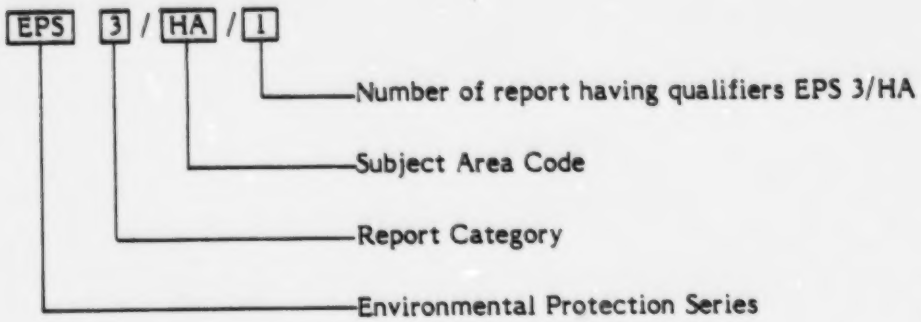

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DETECTION, PREVENTION AND REMEDIATION OF LEAKS FROM UNDERGROUND STORAGE TANKS

by the

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ABSTRACT

Steel tanks have been used for underground storage of petroleum products and derivatives for about thirty years. The oldest tanks have now exceeded their design life and product leaks related to corrosion problems are increasing. The length of the tank's life is one of several factors which could result in a petroleum product leak. These leaks can contaminate soil and water in the immediate surroundings.

The different recovery and treatment techniques applicable to hydrocarbon contaminated soil and water due to underground storage tank leaks are summarized in this report. Detection and prevention are briefly discussed and some examples of available equipment are given.

RÉSUMÉ

Des réservoirs d'acier installés sous terre sont utilisés pour l'emmagasinage des produits pétroliers et de ses dérivés depuis environ trente ans. La vie utile des réservoirs les plus âgés est maintenant dépassée et les problèmes de fuites dû à la corrosion de ceux-ci sont nombreux. L'âge des réservoirs n'est qu'un des facteurs pouvant être responsable des fuites. Ces fuites peuvent contaminer eau et sol environnant.

La présente étude couvre sommairement les différentes techniques de récupération et de traitement applicables à l'eau et au sol contaminé. La détection et la prévention étant directement reliées à l'intervention, elles ont été brièvement discutées. Quelques exemples d'équipement sur le marché sont donnés, lorsque disponibles, pour les domaines de détection, de prévention et d'intervention.

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F. Laperrière
Technology Development and Technical Services Branch
River Road Laboratories
Conservation and Protection
Environment Canada
Ottawa, Ontario
K1A 0H3

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1 INTRODUCTION

During the 1950s and 1960s, thousands of underground storage tanks were installed, mainly for gasoline service stations. The vast majority of these tanks were made from carbon steel and are now approaching the end of their useful lives. Consequently, the incidence of underground leakage is increasing (1). However, it is estimated that less than 25 % of such leaks are actually reported, and in most cases, the the actual losses are substantially greater than the losses stated (2).

Many problems are created when petroleum products leak in the subsurface environment, including: the contamination of potable groundwater aquifers; the creation of explosion and fire hazards when liquid products or vapours enter the lower levels of buildings; and the degradation of utility lines which come in contact with leaked hydrocarbons. The hydrocarbons may persist in the soil for long periods of time either as a film adhering to soil particles or as free oil floating on the water table. If undetected, groundwater and soil contamination could occur for many years and become widespread. Cleanup costs may vary from $25 000 for tank repairs to $90 000 for tank replacement, and up to $1 million if groundwater contamination occurs* (3).

Methods of dealing with leaks once they have been detected are being developed. Tank owners are realizing the importance of prevention and early leak detection in light of the high costs of response. These topics as well as the means of treating soil and water that are contaminated by a leak are examined in this report.

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* Except where indicated otherwise, dollar figures are Canadian (1986).

2 DETECTION

The merits of early leak detection are obvious when one considers the high costs of cleanup and treatment of leaked products, costs that will escalate rapidly if the leak is undetected for some time.

Three approaches are generally employed for leak detection, either individually or in combination: inventory control, periodic testing of tanks, and the use of installed leak detection equipment and sensors.

2.1 Inventory Control

Inventory control is perhaps the simplest and cheapest method of tank leak detection. Product volume in the tank is measured, usually with a dipstick, and compared with the volume delivered and sold. A water-indicating paste is often used on the dipstick to determine if water is accumulating in the tank, which in itself, is a possible sign of leakage.

The main problem associated with inventory control is one inherent in accurately measuring a large volume of volatile liquid. The product in the tank is volatile, therefore some of it will vaporize and occupy the empty portion of the tank as a vapour/air mixture. This mixture may be expelled during delivery and also from expanding as a result of temperature increases (from 0.0007 to 0.0016 volume change per degree Celsuis for petroleum products and 0.0011 for gasoline) (4). This phenomenon should be considered as a source of error when volumetric measurements are taken. In order to minimize this error in measurement, it is important to record the temperature of both the product delivered and that in the tank at the same time before applying a correction factor. A difference of one degree generates an error of 22 L in a 20 000 L gasoline tank (0.11 % error). Another problem is the tank gauging accuracy. The dipstick measurement is the most widely used technique for gauging tanks. Human error in reading the dipstick, assuming a standard and appropriate methodology is used, is about 1 to 13 mm or 13 to 218 L in a 20 000 L tank (0.06 to 1.1 %). The required accuracy on the delivery meters is 0.5 % or 100 L in a 20 000 L tank. A total error of 1.71 % (340 L for a 20 000 L tank) is therefore possible with only one degree difference in temperature readings (5); the error may be greater as the temperature difference increases.

Some errors are not cumulative and will cancel out with time. Mistakes in measurements will not carry over and, if correct procedures are followed, errors in temperature corrections should average out. Leakage will show up in a series of sums as a

definite trend, whereas measurement errors will show up as random fluctuations. Cumulated sums, therefore, should be entered on a graph daily in order to pick up trends. Systematic errors will also show up as trends, so procedures for inventory control must be worked out carefully and be completely standardized (6).

Using inventory control, tank leaks should show up within a month if small (i.e., <0.5 % of tank volume); sooner if large. Investigation of discrepancies which are more than 0.5 % between total metered sales and physical tank inventory measurements should be done on a daily basis, and should include checking pump meters for calibration and determining the possibility of spillage during product delivery or theft. When unsure, tanks and piping should be tested for their integrity (3,7).

2.2 Tank Tests

Although tightness testing will not detect a leak at the time it occurs, it is an integral part of an effective leak detection program. The National Fire Protection Association (8) requires that tests be capable of detecting leaks as small as 0.19 L/h, adjusting for variables (9). These variables are product temperature changes, tank end deflection, product stratification, and vapour pockets.

The average thermal coefficient of expansion for gasoline is 0.0011/°C compared with 0.0002 for water at 17.2°C. If the thermal coefficient of expansion is not taken into account during a tank test, a temperature change in the product can create a false indication of a gain or loss during the test. Specifically, a leak can be concealed by the volumetric expansion of product.

Tank end deflection occurs as hydrostatic pressure within the tank increases or decreases. It causes an "apparent" loss of liquid volume if not corrected for. Product stratification or layering takes place when cool product is added to residual warmer product (or vice versa) forming layers of hydrocarbon at different temperatures. Any test, therefore, must include a method for averaging product temperature differentials because the rate of change will not always be the same. Vapour pockets are strongly affected by changes in temperature and pressure and may give erratic results. They are, however, easily remedied by venting the tank, filling the tank slowly to minimize turbulence, or cooling product down. Finally, a tank test should also have the features of short testing time, portability, ease of operation and low cost (9).

There are several commercial test methods currently available. They include the Hunter Leak Lokator LD-2000, the Heath Petro-Tite (formerly Kent Moore), Ethyl J-Tube Manometer, VacuTect, Horner Ezy-Chek, the helium, hydrostatic, and pneumatic

tests. These tests as well as some others under development are briefly described in Table 1. Only some of them meet the U.S. NFPA requirements. Results on a comparative efficiency evaluation of several leak detection testing methods using an instrumented tank, are available from the U.S. Environmental Protection Agency (EPA). The Petroleum Association for the Conservation of the Environment (PACE) has discussed these test methods in some of their reports and symposia (10,11). In general, it should be emphasized that not only are the hydrostatic and pneumatic tests inadequate in determining if a tank is leaking, but they can actually cause tank and piping ruptures.

2.3 Sensors/Detection Equipment

While an efficient leak test will indicate the status of an underground tank, sensors and detection equipment are necessary for continuous monitoring. Interstitial monitoring in double-walled tanks using fluid or pressure sensors can be used for leak detection as well as wire grids, observation wells, U-tubes and sensors around the tank location (12). There are several criteria that should be kept in mind when selecting a system, including costs, whether the system offers continuous or intermittent detection, sensitivity, effect of normal background levels on the device, resistance to false alarms, ease of maintenance, and whether or not the system can be installed as a retrofit (13). Some of the various types of detectors are listed in Table 2 and some commercially available equipment is listed in Table 3.

TABLE I TANK TESTS

Method	Description	Advantages	Disadvantages	Testing Time	Accuracy (from Manufacturers)	Cost
Pressure Testing (air or other gases)	Tank is pressurized and monitored for air leaks. (1)	- inexpensive - easy	- not conclusive - may cause tank rupture or explosion - may force product out vents		- can only detect large leaks - only reveals whether or not tank is leaking	
Hydrostatic Test (stand pipe test) (performed by pump services and petroleum services companies)	Tank is completely filled and stabilized, tank pressure is raised by 35 to 55 kPa (5 to 8 psig) by a pump or by adding similar hyrocarbon. Leak is suspected if pressure drops by 20 kPa (3 psig) in 15 min.; if pressure is maintained within 1 h, tank is leak free. (3)	- inexpensive - easy	- does not account for temperature fluctuations - may cause tank or piping rupture - tank has to be filled	- 4 h+ for stablization after filling - 2 h for testing	- only reveals if tank is leaking	- $530/tank (U.S., 1986) (3)
Hunter Leak Lokator LD-2000 (formerly Sunmark Leak Lokator)	Principle of tester is based on Archimedes' principle of buoyancy. A hollow sensor filled with the same fluid as that in the tank is suspended from a sensitive balance and partially submerged in the tank. The sensor buoyancy changes in direct proportion to the fluid level changes. Leak size can be estimated by measuring the mass displacement. (3,10,11)	- requires no tank pressurization - can check three tanks simultaneously - tank does not have to be full - compensates for temperature changes within 0.001°C		- 2 h for temperature stabilization before testing - 2 h for testing one tank	- 0.2 L/h	- $500/tank (service station) - $650 to $1000/tank (ind.) and transportation costs ($U.S., 1986) (3) contract service only
Heath Petro-tite (formerly Kent-Moore) (modified hydrostatic test)	Findings based on the amount of product added to an externally connected standpipe to maintain a constant liquid level. A circulating pump is topped up. Temperature of the product is monitored during the test and corrected for. (4,10,11)	- compensates for temperature stratification and corrects for thermal expansion (.003°C) and tank end deflection	- tank has to be overfilled	- 6 h+ for stabilization (or more in cold temp.) - 3 h for testing	- 0.2 L/h	- $350/tank ($U.S., 1986) (3)
Hormer Ezy-chek	A small trickle of air is forced into the top 1.3 cm (0.5 inch) of the product and the pressure required to maintain a continuous flow of bubbles is measured. A change in 0.025 cm (1/100 inch) in liquid level can be recorded. Product temperature is monitored during the test. (3)	- can test two tanks simultaneously - corrects for thermal expansion, temperature stratification (.001°C)	- tank must be full	- 6 h for stabilization after filling - 1 to 2 h for testing	- 0.2 L/h (equipment bought after 1984 only)	- equipment $7 500 - test costs $250 for 1st tank, $200 for subsequent tanks ($U.S., 1986) (3)
Ethyl Tank Sentry (J-tube manometer)	The short leg of a J-tube manometer is filled with an "indicator" fluid while the long leg is filled with the tank fluid (while in the tank). When the tank fluid level changes, some of the indicator fluid is displaced indicating the amount of fluid that leaked out during the test period. (3,10,11)	- can test three tanks simultaneously - tank does not have to be full (fuller tank gives higher accuracy)	- tester completely submerged - tank out of service for at least one day - indicator specifically suitable for gasoline. Use for diesel oil is not recommended.	- 24 h for temperature stabilization before testing - 8 to 10 h for testing	- level change of .05 cm is detected (e.g., a rate of 8 L/h for a 30 300-L tank)	- contract service only

TABLE I TANK TESTS (Cont'd)

Method	Description	Advantages	Disadvantages	Testing Time	Accuracy (from Manufacturers)	Cost
Vacutect (developed by Athabasca Research Ltd.)	The pressure in the tank is reduced by vacuum pumping. Air is drawn through any leaks with the formation of bubbles at the tank wall. As the bubbles detach from the wall, they emit a distinct sound. By interpreting this sound, the size and location of the leak will be known. Auxiliary sensors can detect water bubbles entering when the hole is below the water level. (3,10,11)	- tank does not have to be full - temperature will not affect test - subatmospheric - sensitive - no stabilization delay	- complicated to run - false alarms occasionally - cannot estimate leak rates	- 20 min. for air bubbles testing - 3 h for water intrusion testing	- 0.0006 cm hole diameter	- $400/tank (U.S., 1986) (3) contract service only
Helium Leak Detection System (Smith & Denison System)	The tank to be tested is completely emptied. It is then filled with helium gas at a max pressure of 3 kPa. Any helium leak from the tank or surrounding piping can be detected by means of a portable helium detector in 2.5 cm drilled diameter holes around the tank. (3,10,11)	- accurate - can be used to detect leaks in piping in a separate test	- sensor cannot read through the concrete slab above the tank and along piping - detection time affected by surrounding soil porosity and wetness	- 1 day for preparation - 1 h to 1 day for testing	- 0.2 L/h	- contract services only
PACE Leak Detector (Shell Canada Ltd. for PACE)	The tank is nearly completely filled up to the fill pipe and isolated from atmosphere. A void volume change above the product level in the pipe, due to a leak, will modify the pressure in it. This pressure change is indicated by a difference in liquid level in a manometer inserted in the pipe. (3,10,11)		- tank has to be filled	- 12 h for stabilization before testing - 1 to 2 h for testing	- 0.2 L/h	- not available commercially
Pald-2 Leak Detector (B.C. Research for PACE)	The tank to be tested is over-filled. At least three different pressures are applied using nitrogen to a tube of known cross section mounted on the tank filling pipe. Level changes in the tube are measured with electro-optical sensors, a microprocessor calculates the leak rate. (10,11)		- tank has to be full - interference of soil compaction and traffic vibration	- 1 to 2 h for test (30 min. pressure time doesn't seem adequate for 0.2 L/h leak rate detection) - 6 h+ for stabilization before testing	- 0.2 L/h	- not available commercially
Laser Beam Leak Detector (SRI International for API)	Measures the change of the tank surface level over time using two laser beams reflected by cube corners sitting on floats in a tubing system in the tank. The leak rate is obtained from a microprocessor. (3,10,11)	- compensates for temperature changes - tank does not have to be full	- sophisticated system	- 1 day for preparation - 3 h for testing	- 0.4 L/h	- not available commercially
Mooney Tank Leak Detector	A capacitance floating probe measures the level changes in the tank fill pipe after adding and retrieving a known amount of liquid. Using temperature fluctuations, level changes are calculated and compared to measured ones to determine the leak rate. (3,10,11)	- compensates for temperature	- tank has to be filled	- 12 h for stabilization after filling - 1 h for testing (38)	- 0.2 L/h - can measure 0.25 to 0.50 mm in level changes	- equipment $3800 ($U.S., 1986) (3)

TABLE 2 TYPE OF DETECTORS (13)

Type of Detector	Detects	Description	Remarks
Catalytic	Vapour	Measures the resistance change when hydrocarbons are burned with oxygen on a catalyst-coated wire.	- sensitive to a limited range of concentration above 200 ppm - responds rapidly - requires periodic recalibration - some gasoline components (e.g., lead alkyls) contaminate them; some contamination-resistant sensors are becoming available
Semiconductor	Vapour	Measures resistance change when hydrocarbons adsorb on conductor surface layer.	- operate over a wide concentration range (most effective at 2000 to 20 000 ppm) - inexpensive - present manufacturing makes them noninterchangeable
Flame Combustion	Vapour	Measure temperature rise when hydrocarbons burn in a propane flame.	- poison resistant - require high maintenance, replacement of propane fuel - expensive
Thermal Conductivity	Liquid	Differentiates between liquids by measuring the rate of cooling of a heated thermistor.	- can distinguish between air, water and hydrocarbons - not sensitive to layers of hydrocarbons less than 0.64 cm - can be fouled - older method, more documentation exists for it
Electrical Conductivity	Liquid	Measures electrical conductivity with two probes	- low cost - less proven
Optical	Liquid	Measures optical density across a liquid gap or refractive index outside an internal reflection cell	- lower sensitivity than some methods
Cable Degradation By Hydrocarbons	Liquid	Conductors degrade upon contact with liquid hydrocarbons. The resultant short circuiting of the system causes an alarm to sound.	- time taken for alarm to sound, varies upon the nature of the hydrocarbon and the environmental conditions - background hydrocarbons cause false alarms
Surface Acoustic Wave (SAW)	Vapour	Sensor absorbs vapours with a resonant microcircuit containing a SAW plate. The absorption changes the resonant frequency.	- highly sensitive for some gases - potentially low cost, continuous hydrocarbon detection
Ambient Air Monitoring	Vapour Liquid	A monitoring well is sunk into the tank backfill into which a perforated pipe is placed. Leaks are detected by vapour detection devices or sampling.	- inexpensive - easy to install and operate - well can be used to determine groundwater flow
Ultrasonic	Flaws in tank or piping	Ultrasonic reflections from external or internal surfaces of tank are received and recorded. Two- and three-dimensional pictures are produced, giving length, geometry and depth of anomalies	- used primarily for piping but can easily be applied to tanks - systems range from hand-held scanner to those installed in tanks - comparative technique - system must be calibrated but standards can vary from test to test - noise levels can affect test results - personnel must be trained in order to correctly interpret data

TABLE 3 COMPARISON OF SOME COMMERCIAL DETECTORS

Type	Device	Remarks*	Cost*
Degradable Cable	Orbmah sensor cable (Total Containment)	- cable must come into contact with the hydrocarbon to cause alarm to sound - once contact is made, alarm sounds in 40 min. (in gasoline) - time to alarm longer for more viscous hydrocarbons and at lower temperatures - cable must be repaired after alarm and is affected by background hydrocarbons	- $1200 (kit for a 4-tank installation) ($U.S., 1985)
Thermal Conductivity	Pollulert FP-102 System (P.R. Mallory & Co.)	- installed in underground well alongside tank (detects liquid hydrocarbon - 0.3 cm thickness - floating on groundwater) - alarm sounds 0 to 5 seconds after sensors covered - probes reusable	- $500 to $800 for probes - $1100 to $1200 for control unit - $5500 for the system (tank and filling line) ($U.S., 1985)
Semiconductor	Soil sentry (Genelco, Inc. - Patent Pending)	- fully automatic underground leak monitoring system - vapour samples drawn into unit by an aspirator pump - alarm activated when vapour samples are above a threshold level or when extremely high vapour level detected	- $100 for probe - $5000 for gas detector ($U.S., 1986)
Optical	OPW/OLLS optic liquid level sensor	- although developed to monitor liquid level in tanks, it can be used for detection in much the same manner as the Pollulert system - automatic and continuous monitoring - no electrical energy involved	- $200 to $250 for sensors - $815 to $1700 for monitor - about $3500 for a system (tank and filling line) ($CAN., 1985)

* From manufacturer

3 PREVENTION

Although an effective leak detection system is an integral part of a leak prevention program, the true solution to underground leakage is the prevention of leaks rather than detection after the fact. Consideration must be given to the corrosion protection of the tank and underground piping, and to the prevention of operational overflows and discharges. A predictive analysis for the aging of the tank should also be included in a prevention program.

Prevention and secondary containment are briefly discussed in this section. While secondary containment is not a means of actually preventing leakage, it is a method of preventing product from spreading over a large area.

3.1 Corrosion

Many underground tanks installed in the 1950s and currently in service are made from bare carbon steel and are therefore subject to corrosion. Corrosion, resulting from the interaction between tanks and piping and their surroundings, both internal and external, is the most common cause of tank failure. Tank material is obviously important, but corrosion can be accentuated by improper installation practices. For example, scratches on the surface of coated steel tanks incurred during installation will lead to accelerated localized corrosion (1).

Preventive measures should be taken to avoid corrosion. Three basic methods can be used: cathodic protection, interior and exterior coatings, and use of non-corrosive materials. In addition, surveys should be conducted that, given soil conditions and tank age, can determine the likelihood of a tank leak and when it may occur.

3.1.1 Cathodic Protection. There are four requirements necessary if corrosion is to occur: an anode, a cathode, an electrolyte and an electrical current to complete the circuit. Cathodic protection works by transforming the tank into the cathode, or protected element, thereby reversing the effect of corrosion. There are two types of cathodic protection: galvanic (or sacrificial) anode and impressed current. A typical cathodic protection system for a 15 000-L existing tank would cost approximately $625.00 ($Can., 1981) (13). The installed cost of a new coated steel tank with a cathodic protection is about 10 % higher than that for a bare tank.

Sacrificial anode. Several metals (e.g., magnesium, aluminum and zinc) have a higher tendency to corrode than steel. When connected to a steel tank, these metals

become the anode and corrode preferentially to the tank which becomes the cathode. The number of anodes required for a tank depends on the soil conditions. A soil with lower resistivity is a better conductor causing the anode to be capable of greater output. In the case of magnesium anodes, this results in a short anode-life expectancy. Coating the tank with a good dielectric coating, however, can reduce the number of anodes needed and is required in ULC - S603.1M Standards*. With this system, the tank must be electrically isolated from structures, but can be easily monitored at ground surface test stations. This system is generally used for new tanks because of the electrical insulation and coating requirements for economic operation (13).

Impressed current. An external power source and semi-inert anode materials are used for this technique. A current from a commercial power source through a DC rectifier is impressed into the soil through ground semi-inert anodes, typically graphite, high silicon cast iron or platinum-clad metal substrates. Not only can this system be used to protect uncoated and uninsulated existing tanks when applied prior to extensive corrosion, but the voltage can be varied for different soil and groundwater conditions. This method is more costly as a protection system for a new tank (approximately $1250.00 ($Can., 1981) for a 15 000-L tank in addition to continuous power costs (14)) than the sacrifical anode system but is cheaper than the replacement of a tank. There is, however, a possibility that neighbouring underground installations may be damaged. It is also possible that the current may be accidentally switched off, thereby eliminating the protection (13).

3.1.2 Interior and Exterior Tank Coatings. Coatings alone do not provide adequate protection, but they serve well as a form of corrosion prevention when combined with cathodic protection. If pinholes exist in the coating, however, the exposed metal will be subject to accelerated localized corrosion. Even with cathodic protection, imperfections in the coating lead to shorter anode life spans or increased current requirements for impressed current systems. A coating should be highly resistant, therefore, and it must be applied so that it provides complete coverage. Tanks must be handled with care during installation to avoid damage. The coating must be inspected and patched (with the same material) on site before and after the tank is positioned in the hole (11).

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* Underwriter's Laboratories of Canada standards for the installation of underground tankage.

Types of tank coatings and linings include: asphalt, epoxies, fiberglass-reinforced plastic, silicones, rubber, polyethylene, and concrete (1,3). Most commonly, a 0.3 to 0.4 mm coating of coal-tar epoxy is used. This coating can be applied cold by spray or brush, requires no special primer and has excellent adhesion, excellent resistance to gouging and scratching, good durability, and good resistance to gasoline. However, it has a limited pot life and requires meticulous surface preparation (11). The coal-tar epoxy costs from \$1.50 to \$2.25/ft^2 compared to \$7.00 to \$8.00/ft^2 (\$Can., 1986) (Marclin Industries) for a spray-on glass (fiberglass) liner. Concrete and rubber can also be used, but both are prohibitively expensive and rubber has only limited resistance to hydrocarbons.

The type of coating chosen and whether it is to be applied on the interior or exterior of the tank depends on how much a tank owner can (or is willing) to spend. It must be remembered, however, that the lining must meet certain minimum requirements and installers must adhere to comprehensive field lining application procedures. Most importantly, the tank must be sound if a coating is to be applied.

3.1.3 Tanks. Materials available for tank manufacture are listed and discussed briefly in Table 4. There are standards regarding installation and conditions for underground steel storage tanks (Underwriter's Laboratories of Canada; ULC S603 M81 and S603.1 M82) and for reinforced plastic ones for petroleum products (ULC S615 M83). In addition, new materials, such as "K-crete" aggregate that can provide 100 % compaction when used correctly should be further investigated for backfill material.

3.1.4 Corrosion Surveys. The lifespan of an unprotected, bare, steel tank can vary from five to 50 years or more (15), the environment surrounding the tank having a large effect upon this figure. It is recommended, therefore, that a corrosion survey on tanks be conducted before undertaking upgrading measures. By correlating tank age to tank environment, the likelihood of failure due to corrosion and when it may occur can be estimated. Such a study should be conducted either before or at some point soon after underground tanks are installed. Two of the available study methods are described in the following.

One approach developed by a PACE Task Force uses a tank/soil index as the main criterion in the evaluation procedure. This number is the product of tank age and the soil aggressiveness value. The soil aggressiveness value is computed through a point system that includes soil resistivity, pH, soil moisture content, presence of sulphides, and differential values of them. A survey of tank leaks from all Canadian petroleum

TABLE 4 COMPARISON OF DIFFERENT TANK MATERIALS

Type of Tank	Remarks on Installation	General Remarks
Steel	- care should be taken with backfill it should contain no cinders or foreign matter than could become cathodes in a corrosion cell - backfill must be tamped down and tank anchored	- bare steel tanks corrode; under some conditions the tank may fail within five years of installation - Costs for a 15 000-L tank: bare steel: $1800 with corrosion protection: $2600 ($Can., 1986) (Marclin Industries)
Fiberglass Reinforced Plastic (FRP)	- backfill provides 90% of tank support (circumference and ends); use sand, pea gravel (50) - extra care on installation in frozen ground or high water table conditions (14)	- corrosion resistant, no maintenance (14) - compatibility of the stored product with the tank is important - repairs are allowed - reuse is allowed once excavated after proper testing - costs for a 13 600-L tank: $3800 ($Can., 1986) (CAE) installation cost: about $1000 more than for a steel tank Note: no significant difference in price between FRP and ULC 603.1 tank as tank capacity increases (14)
Fiberglass Reinforced-Plastic-clad Steel	- installation essentially same as for steel except no cathodic protection is necessary and care must be taken not to puncture fiberglass (100-mm thick) (3)	- used primarily when storing abrasive products - possibility of bonding breaking due to different expansion rates of fiberglass and steel
Double-walled Steel	- installed same as single-walled steel tank - generally installed with protective coatings (fiberglass) or cathodic protection	- vacuum or pressure is maintained in annular space between inner and outer wall; loss of vacuum (or pressure) (perforation) is signaled by a monitor - cost twice as much as a single-walled tanks ULC 603.1 (14) - used where environmental safety hazards are high
Concrete	- generally are constructed directly on site (hole is dug, mold is made and concrete is poured into hole) - ground movement, frost conditions must be taken into account	- presently are extremely expensive - when used in combination with impermeable liners, provides a very good means of storing hydrocarbons (long life, corrosion-proof)

companies indicated that sites where the tank/soil index was <69 accounted for only 5 % of the tank leaks due to corrosion; sites where the tank/soil index was ≤180 accounted for 40 %; and, sites where the tank/soil index was >180 accounted for 60 %. Appropriate remedial action was recommended based on the tank/soil index.

1. at a tank/soil index <69, an environmental risk analysis should be conducted;
2. if the tank/soil index is between 69 and 180, leak testing should be performed; and
3. at a tank/soil index >180, the tank should be replaced (11).

The other method developed by Warren Rogers Associates Inc. for the American Petroleum Institute (API), estimates the tank age at which failure occurs due to external corrosion from physical site measurements (e.g., soil resistivity, moisture, sulphides and tank size), used in a mathematical equation. Probabilities and confidence limits for specific ages may then be calculated; the age of a leaking tank assumed to follow a normal distribution. An equation for the prediction of internal corrosion induced failures, including the average age at failure and the probability of tank failure at any specified age for a given volume of sales and refill rate was also developed (3,11).

3.2 Secondary Containment

A major difficulty encountered in response to underground leaks is that the product can, depending on the soil type and water table level, contaminate enormous quantities of soil and water. This problem can be reduced by installing a secondary containment system to confine the contaminant to a smaller area. There are several means available: double-walled tanks, liners, barriers and concrete vaults.

3.2.1 Liners. Natural (clay) or synthetic (membranes) liners can be used. Of the membranes available commercially, those compatible with hydrocarbons and suitable for secondary containment were made from: urethane ethers and esters, and high density polyethylene. Other liners made from chlorinated polyethylenes, polyvinyl oil resistant chlorides, butylrubber, chlorosulphonated polyethylenes, neoprene, ethylene, and propylene diene monomer have poor resistance to hydrocarbons or to severe environmental conditions and would be ineffective for secondary containment (16,17,18,19). Of these materials, high density polyethylene is resistant to the greatest diversity of chemicals including those commonly used as additives in hydrocarbon products. High density polyethylene can be purchased in thicknesses ranging from 10 to 100 mil (0.254 to 2.54 mm), the choice of which will depend on cost considerations, handling, and type of

product to be contained. The membrane can either be placed directly onto the backfill or can be wrapped around the tank. In the former case, there are two configurations commonly used. One involves burying thick (100 mil) high density polyethylene in the backfill but the membrane is manufactured in 7-m wide sheets and handling is difficult. Other problems with membrane use may occur. High temperatures may cause membrane breakdown, specialized application skills are needed (the membane must be welded). The thick membrane is not as flexible and easy to manipulate as the thinner grades, and sharp objects must be removed from the tank backfill to prevent puncturing of the membrane.

The second configuration consists of a thin (i.e., 20-mil) membrane sandwiched between two geotextiles (synthetic fabrics used for soil-related construction or geotechnical applications). Geotextiles are strong and porous, they provide the strength and support. The high density polyethylene acts as a barrier to hydrocarbons. No technicians are needed to install this system and, because the membrane is protected against tearing, less care needs to be taken with the backfill.

Alternatively, a membrane (typically high density polyethylene) can be welded around the tank. The tank is first wrapped with a mesh-like material to protect the membrane and to provide a space between the tank and membrane. A leak detection system and a device to maintian the pH at a constant level are installed in the annulus. The latter is necessary as there will inevitably be some water in the annulus which could cause tank corrosion if the pH became too low. The leak detector should be installed in such a way that, should it become necessary to remove it, the tank need not be excavated. Some type of sleeving could also be put on the pipes leading to and from the tank.

3.2.2 Barriers. There are several types of barriers. Clay barriers are the least expensive but are subject to cracking, especially due to ground movement. Other vertical barriers are made from a number of materials, including: admixtures (slurries) of soil-bentonite and cement-bentonite and variations thereof as well as asphalt-based emulsions; plastic-concrete or lean-concrete cutoff walls; diaphragm or rigid concrete walls; freezing localized areas in the subsurface (generally only for short-term applications); sheet pile walls or interlocking panels driven into the ground; and, more recently, synthetic membranes. Installation usually involves either trenching, suspension or chemical grouting (the pressure injection of a semi-liquid or slurry type material "grout" into the voids or fractures of porous or fractured geologic media) or the vibrated beam technique. Problems exist with slurry barriers in that the installation procedure can be

difficult, the integrity of the barrier cannot be easily verified during or after installation, and sampling the barrier material may in itself damage the barrier's integrity (20).

3.2.3 Vaulting. Vaulting is perhaps the most secure method of secondary containment — and the most expensive. A concrete vault is installed in the ground and the tank is placed inside it and the proper backfill material added. Monitoring devices can be installed in the vault and a concrete roof equipped with manholes is then placed over the entire structure. This method of containment is for use in high risk areas (e.g., urban areas or those with very permeable soils).

3.3 Other Methods

Human error is responsible for a large proportion of underground tank "leaks". A sophisticated detection and prevention system is useless if no means are taken to protect against accidental spillage, especially that which may occur during product delivery. Methods of accomplishing this could be achieved by installing one of the following in the delivery line: an automatic shutoff control system with a sorbent material packing that can handle a limited volume of overfill or spillage, or an oil stop valve.

3.3.1 Imbiber Valve. Imbiber beads are spherical plastic particles that absorb a wide range of organic liquids. The fluid is actually absorbed into the polymer network of the bead, and cannot be squeezed out once imbibed. With some organic fluids, these polymer particles can imbibe up to 27 times their original volume and, in the process, swell three and one-half to four times their original diameter. When these beads are placed within a valve, they permit water to pass but will swell and prevent flow when in contact with hydrocarbons. Such a valve connected to a secondary containment overflow pipe provides the extra protection necessary for accident prevention. The valves themselves are not expensive (approximately $1.00 each), but replacement can be messy as the activated beads are sticky and difficult to clean. A new device that incorporates Imbiber Beads is now available and should ease the replacement of an activated unit. The colour of this device changes when activated to indicate leakage (see Appendix A: Emco, Anco).

3.3.2 Oil Stop Valve. Whether a tank is leaking or accidental spillage occurs, discharge to sewers must be prevented. An oil stop valve that can differentiate between oil and water (by means of differences in specific gravity) should be installed in outlets to sewers if this is a potential problem. While the stop valve will not prevent spills, it will aid in containing them.

4 RESPONSE

4.1 Initial Action

A leaking underground storage tank presents special problems for cleanup because the pollutant is "spilled" underground. Traditional response equipment such as dispersants, skimmers and sorbents are not usually applicable. For the most part, initial action involves locating the source of leakage and discovering the extent of the spill after taking the necessary precautions to protect life and property. This can become quite complicated as the pollutant can travel for miles underground through porous soil and rocks, trenches filled with porous material, along pipes or conduits, or through sewer pipes.

There are three main steps to follow in locating the source and extent of an underground spill. First, information must be obtained on the physiochemical properties (density, solubility, volatility, etc.) of the pollutant as well as its chemical composition, as these properties may affect the manner in which the pollutant migrates. Volatile hydrocarbons can cause particular problems as the accumulation of vapours in the ground and in buildings can create explosion and health hazards.

The second step involves determining the source of the pollutant. Some potential sources to check are listed in Table 5, given that the leaking product is a hydrocarbon. There are, however, two important factors to consider. First of all, liquids can travel very slowly underground, or sometimes not at all unless the water table rises. There can be a considerable time lapse, therefore, between the occurrence of a leak and the appearance of liquid or vapour. With this in mind, all history or evidence of potential sources should be recorded in an investigative report regardless of how long ago the leaks occurred. No potential sources should be eliminated on the basis of time until analysis of available data justifies doing so.

The third step involves determining the weathering of the product, including: the vaporization of the volatile fraction (olefins, paraffins); the dissolving of some constituents (especially aromatics (benzene, toluene, xylene) for gasoline (21)) in water; the decomposition of the hydrocarbon by bacteria; and the oxidation of olefins in the presence of sunlight. Weathering can make the identification of the product difficult, but it can also provide information on the length of time a known product has been in the ground and the direction of migration (22).

TABLE 5 POTENTIAL LEAK SOURCES

1.	Gasoline service stations.
2.	Automotive garages or agencies.
3.	Fleet operators (e.g., cab companies, dairies, and municipal garages) and railroad terminals.
4.	Fuel distributors that supply service stations or commercial users.
5.	Heating oil distributors.
6.	Contractors, equipment dealers who may store fuel on the premises.
7.	Chemical companies (includes refineries).
8.	Airports and marinas.
9.	Industrial plants that may use or store flammable or combustible liquids.
10.	High pressure petroleum or gas lines in the area.
11.	Any other properties on which flammable or combustible liquids may be stored (include abandoned storage sites, private residences, government properties).

To simplify the investigation, there are some key questions that tank owners or operators should be asked (Table 6). If inquiry does not reveal any potential sources, the owner or operators may be able to assist in checking the equipment and area around their premises. When cooperation is not forthcoming, the help of government or municipal authorities may be needed.

There are several signs to look for when examining facilities and equipment. Saturated or darkened soil, and stained or disintegrated concrete all indicate repeated spills. Above-ground tanks, fillpipes, other exposed piping, pumping equipment, floor drains and sumps should all be checked for the signs that may suggest a leak or overfilling. If an underground tank is leaking; however, the only means of determining this may be by a tank test or the excavation of the tank. If contaminants are traced to a property containing underground tanks, therefore, a tank test should be conducted. Signs to look for on the grounds and adjoining areas include sheens on nearby streams and bodies of water, damaged vegetation, vapour in sewers and other underground cavities, and signs of product seepage through the soil at excavations. If a leak is detected, the tank owner should immediately empty his tank of all product and suspend use of the tank.

Often the source of leakage is not readily apparent. Hydrogeological investigations and conductance measurements can be used to determine its location. These methods will also enable the extent of the pollution to be traced. First, a

TABLE 6 QUESTIONS TO ASK TANK OWNERS OR OPERATORS

- Have there been any spills during loading or unloading?
- Is storage or handling equipment leaking, or has there been a leak? (Check for excavations that may have damaged underground facilities or evidence of repair work.)
- Has any maintenance work involved the release of product from tanks, pipes or other equipment?
- Have there been signs of odour or liquids where they should not be?
- Have inventory records been kept?
- Has any water been found in underground tanks?
- Do they have any knowledge of accidents in the area that may have released product from tank trucks, barrels, large fuel tanks? (Local authorities, e.g., fire officials, may be helpful in this case.)
- Have there been any pumping problems?

geological map of the area must be obtained (the easiest and cheapest way of accomplishing this is through the Geological Survey of Canada). Then a hydrogeological survey may be conducted by drilling a series of boreholes in areas around the plume until the extent and location of the spill are pinpointed. The geological map will aid borehole placement by indicating to responders the most probable areas of hydrocarbon seepage. It must be kept in mind, however, that fluids can "flow" uphill when underground and will trace an extremely tortuous path when travelling through fractured rock. For example, it is possible for the fluid to travel in one direction and then double back, following different fracture lines in the rock. In urban areas, hydrogeological investigations suffer from severe restraints. These include inacessibility of areas occupied by buildings and other fixed structures, restraints on mobility of equipment by the location of fixed structures, restraints on the locations of test-holes or trenches, and hazards to drilling and trenching equipment posed by above or underground services (e.g., utility lines). In addition, damage to paved surfaces, vegetation, fences or retaining walls, disruption of traffic patterns, and increased noise will increase the cost of investigation and/or present annoying disturbances to the public.

The selection of drilling equipment to be used in a hydrogeological investigation in an urban area will depend upon the type of ground material to be drilled, depth of testholes desired, and manoeuvrability. The main types of equipment and methods available are listed in Table 7 (23,24). The corkscrew action of the auger-type

TABLE 7 DRILLING METHODS AND EQUIPMENT

Drill Type/ Method	Hole Diameter (cm)	Maximum Hole Depth (m)	Average Time Per Hole	Cost	Advantages	Disadvantages
Stem Auger	10 to 51	9 to 15	Fast (under suitable soil conditions).	Inexpensive to moderate.	- widely available - mobile - can obtain dry soil samples while drilling	- caving in unsuitable soils - good only for fine-coarse unconsolidated soil - test wells cannot double as recovery wells
Hollow Stem Auger	10 to 51	9 to 15	Fast (under suitable soil conditions).	Inexpensive to moderate.	- good for sandy soil - casing can be set through hollow stem - can obtain dry soil and split-spoon samples - controls caving	- casing dia. limited to 5 to 8 cm O.D. - good only for fine-coarse unconsolidated soil - test wells cannot double as recovery wells
Kelly Auger	20 to 122	27	Fast	Moderate to expensive.	- can install large dia. wells - drill holes with min. soil wall disturbance or contamination - can obtain good soil samples	- large equipment seldom available in rural areas - casing may be required while drilling
Bucket Auger	30 to 183	27	Fast	Moderate to expensive.	- can obtain good soil samples - can install large dia. wells	- hard to control caving - must use drilling fluid occasionally - large operating area normally required
Rotary	10 to 15	Unlimited	Fast	Expensive	- good for deep holes - can be used in consolidated soils and relatively soft rock - wide availability - controls caving	- drilling fluid required (may damage borehole) - drilling water supply required
Cable Tools	10 to 41	Unlimited	Slow	Moderate to expensive.	- can obtain good soil samples - can install large dia. wells	- slower than other methods - hole often crooked - may need casing while drilling
Air Hammer	10 to 30	Unlimited	Fast	Expensive	- fast penetration in unconsolidated rock	- inefficient in unconsolidated soil - noisy - dust/air release - excessive water inflow will limit use
Casing Driving (well point)	5 to 61	18	Slow to moderate.	Inexpensive	- very portable - readily available	- limited to unconsolidated soil - cannot penetrate large rocks, boulders, bedrock - difficult to obtain soil samples - test wells generally cannot double as recovery wells
Jetting*	5 to 61	30	Slow to moderate.	Moderate	- readily available	- limited to unconsolidated soil - difficult to obtain soil samples - test wells cannot double as recovery wells
Dug Wells	Unlimited	3 to 6	Fast	Inexpensive	- readily available - large dia. hole easily obtained	- caving can be a severe problem - limited depth - explosive hazard when excavating into hydrocarbons

* A high pressure hose is attached to a length of casing which is forced downward through soil by the jet action of the water.

methods causes the samples to be highly disturbed and considerable mixing of cuttings occurs during their travel to the surface. Cuttings from rotary equipment tend to be generally undisturbed and more representative of the actual drilling depth. Manoeuvrability of equipment may also be a significant problem in urban areas. Once boreholes have been drilled, they may be used for groundwater sampling. Some of the commercially available samplers and measuring devices are listed in Table 8.

Terrain conductivity measurements can be used to map subsurface soil contamination. The instrument used can distinguish underground pollutants from soils and groundwater by their different dielectric properties. Soil contact is not required and the number of borings and/or observation wells required can be reduced. There are portable one-man units available, effective to a depth of 6 m; larger two-man instruments can survey to a depth of 60 m. Conductivity measurements can not only detect the presence of hydrocarbons but they can be used to estimate the thickness of floating hydrocarbon pools. Again, this method is severely hampered in urban areas. Objects such as sewer lines, water mains and power lines as well as surface objects can interfere with conductivity measurements, usually by increasing measured values. These interferences can be overcome by changing the orientation of the meter and/or by using the buried or surface object as a "constant". When used in conjunction with a hydrological program, terrain conductivity measurements can improve the accuracy of the spill investigation and can reduce overall costs by reducing the number of monitoring/observation wells needed (25).

4.2 Long-term Response

Once the source of a leak and its extent have been determined and the necessary safety precautions taken, the cleanup and recovery can begin. Since many factors affect migration and recovery, no single system will work for every case. Often, recovery systems utilizing a combination of equipment and techniques must be tailor-made for a particular leak. Moreover, these operations are frequently long-term; that is, involving periods of years.

There are some factors, that if considered beforehand, can prevent problems later on during the recovery operations (Table 9). Some of the general methods and equipment available to recover and treat underground contaminants are outlined in the following section. In addition, it is strongly recommended that someone trained and experienced in this field be consulted prior to undertaking the recovery program, because

TABLE 8 GROUNDWATER MEASURING DEVICES

Device	Description	Remarks
Oil Recovery Systems Surface Samplers	- acrylic or Teflon tube sealed with ball checkvalve (Delrin for acrylic-type, Teflon for Teflon type) - has 7.6 m of anti-static, mildew resistant lowering resistant lowering cord - acrylic type is clear and calibrated in inches and centimetres	- measures depths to 30 m with reel controlled tape Costs: 30 cm* acrylic sampler $ 75.00** 102 cm acrylic sampler $ 95.00 40-cm double-ended acrylic sampler $ 98.00 30-cm teflon acrylic sampler $ 85.00 61-cm teflon acrylic sampler $115.00 91-cm teflon acrylic sampler $145.00 PVC carrying case $ 9.95 Tape reel assembly-- 15 m $ 59.50 -- 30 m $ 65.60
Oil Recovery Systems Interface Probe	- obtains water levels and can determine oil/water interface - consists of dual sensing probe, optical liquid sensor and uses electrical conductivity to distinguish between hydrocarbons and water - battery operated	- 15, 23, 30 m tapes available - Probe sizes of 15, 23, 30 cm (in length, 1.5 cm dia.)
Well Point Sampler (K-V Associates Inc.)	- series of 1.6 cm stainless steel tubing - pounded into ground and sample taken with with suction pump	- non electronic - work to 3 to 7 m depths - cost: $950.00
Nepcco Liquid Samplers	- acrylic and Teflon samplers available - similar to oil recovery samplers - any length available upon request, 11 m of non-sparking lowering cord included	Costs: 36-cm acrylic sampler $ 69.00 56-cm acrylic sampler $ 82.00 107-cm acrylic sampler $ 89.00 61 cm x 2.5 cm OD Teflon $149.00 61 cm x 4.4 cm Teflon $269.00 PVC carrying case $ 4.25
Nepcco Hydropurge and Petropurge Probes	- petropurge probe for liquid hydrocarbons (oil, gas, solvent) thickness assessment - hydropurge probe for sensing oil-water interface	
Bat Groundwater	- consists of a filter tip attached to a 2.5 cm diameter extension pipe made of steel or plastic - different test adapters make tight, temporary connection to filter tip with aid of a hypodermic needle - samples taken by lowering adapter down connection pipe pushing needle into rubber disc in filter tip liquid sucked into container via filter tip due to pressure difference - filter tip designed for one-time installation only.	- no air contact or external contamination - volatile components can be accurately sampled - to install: - push into soft soils - push and use hollow stem auger for hard soils - drilling, sand packing, sealing with bentonite for solid rock - depth of use: 0.5 to 60 m (max. known to 400 m) - no human contact with soil or fluids Costs: Filter tip (STD) $268.00 Basic sample kit (50 filter tips) $2000.00 Core pressure kit $6350.00 Permeability kit $2670.00

* refers to length of sampler
** prices in American dollars unless otherwise specified

TABLE 9 AVOIDING COMMON PROBLEMS DURING RESPONSE ACTIONS

Consider that:

- Mobile product seeks any escape route, be it sewer lines, underground utility lines or vaults, drain fields or basements as it moves down to the water table or other natural barrier.
- The source of the leak will continue to contribute to hazardous conditions and/or environmental pollution until it is eliminated.
- Test wells must be installed deep enough into the water table to determine both the product and the water level.
- A well screen or properly perforated pipe will ensure the accurate measurement of product on the water table.
- The proper use of gravel packing during the installation of recovery or test wells will ensure the efficiency of the wells.
- Whether the dewatering for a come of depression will contaminate additional areas or create problems in adjoining buildings must be determined before a recovery well is installed.
- The necessary approvals must be obtained for the disposal of wastewater produced from the recovery wells.
- Recovery wells that both contain and recover the mobile product will be more efficient.
- The equipment used must be appropriate for the recovery project or increased costs and/or excessive losses of time will be incurred.

an incorrectly applied program may not only be ineffective, but it may worsen the situation.

4.2.1 **Groundwater Recovery.** In the majority of tank leaks, the product reaches groundwater, either by seeping or being washed (usually by rain) through the soil. Once this occurs, the hydrocarbon will move with the flow of groundwater thus contaminating a larger area. In order to recover the product, one must intercept and halt its flow. This may be done either by removing the oil as it collects in cavities dug to the groundwater surface or by actively pumping out the groundwater. The latter method creates what is known as a cone of depression (Figure 1). Any free oil in the cone of depression will flow under gravitational forces to the bottom of the cone where the layer of oil deepens and can be recovered. Success of this method depends on maintaining the artifical gradient on the groundwater surface.

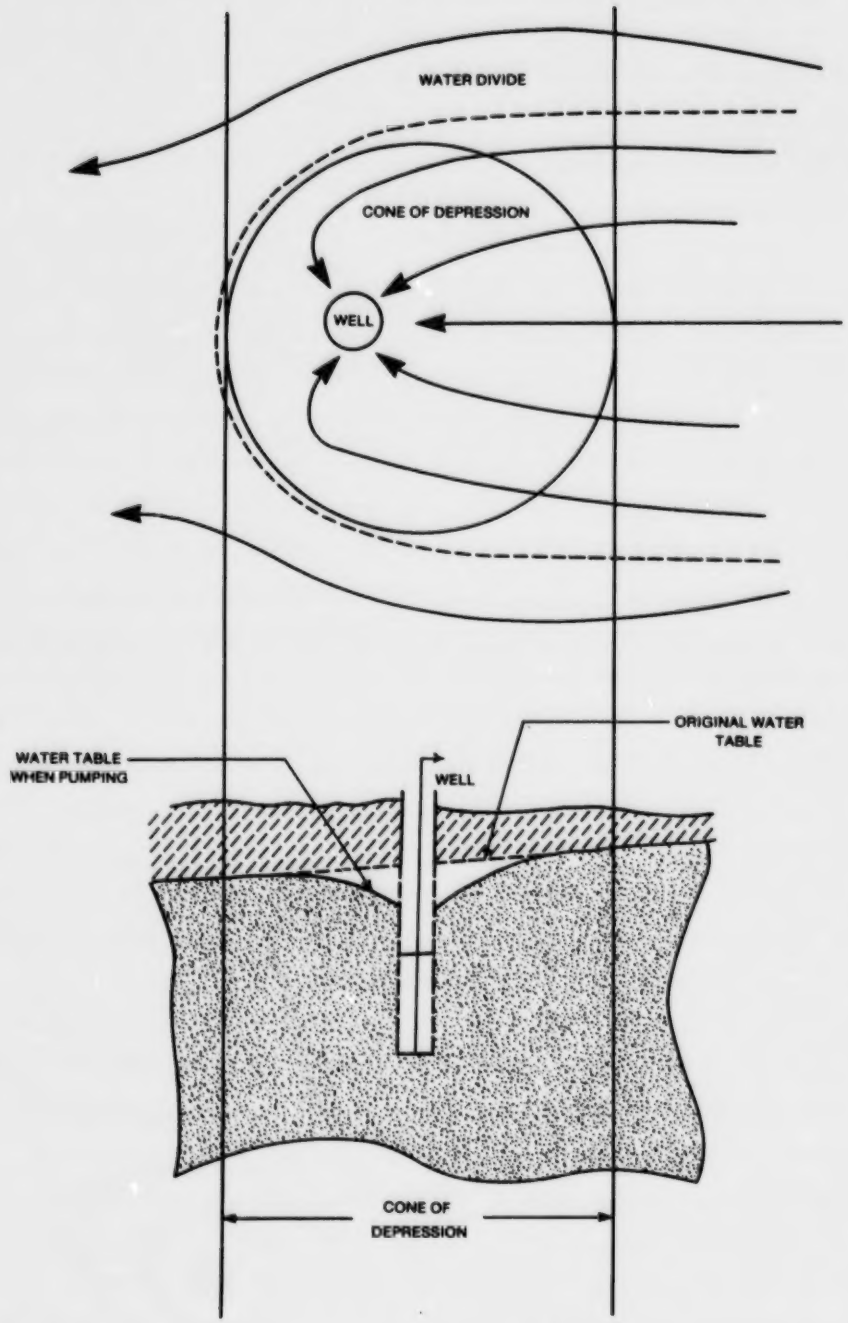

FIGURE 1 CONE OF DEPRESSION FORMED BY PUMPING (23)

The type of recovery method chosen will depend on several factors:

- the amount and type of oil in the ground;
- the extent ot which oil has spread on the water table;
- the nature of the oil layers in the region of the spill;
- the position of the water table;
- the soil and rock formations in the area;
- access to recovery wells/trenches for maintenance; and
- economics.

The optimum operation will be the one that removes the greatest amount of oil with the minimum lowering of the water table. This is important since free oil will seep through soil that, previous to the pumping operation, was saturated with water and therefore uncontaminated. The total pumping rate necessary to create the recovery cone(s) depends on the characteristics of the aquifer, and can be derived from pumping tests. When the required pumping rate is too high for one well, several wells can be operated as a battery. If several partially penetrating wells are used rather than one well alone, there will be a more rapid removal of oil during the initial stages of recovery and additional soil contamination will be kept to a minimum as the water table is lowered (26).

Trenches and ditches. The use of trenches and ditches is a very good means of intercepting the leaked product; however, it is only practical when the water table is no deeper than approximately 3 m. This limitation is imposed by the ditching equipment available, the extent to which the soil will support the walls of the ditch without caving, and the amount of soil that must be removed. For example, ditches in unconsolidated soils must have gently sloped walls; therefore, an inordinate amount of soil must be removed relative to the depth of the ditch. Soil supports such as boarding can also impair the flow of oil if installed horizontally rather than vertically in the ditch.

An intercepting trench should be constructed across the entire front of the migrating body of oil and should be as close as possible, without damaging basements or foundations, to any building into which the product has entered. The width of the ditch need only be wide enough to accommodate the necessary pumps and product removal devices. An impermeable liner, though usually unnecessary, may be installed on the downstream wall to prevent the onward flow of oil, but still allow water to pass. In practice, the equalization of hydrostatic pressure on both sides of the sheet tends to make the sheet float away from the wall, and the oil tends to find its way around the end of the liner in any case. Moreover, the continuous removal of water and oil from the trench depresses groundwater on both sides, preventing further migration. Even without water

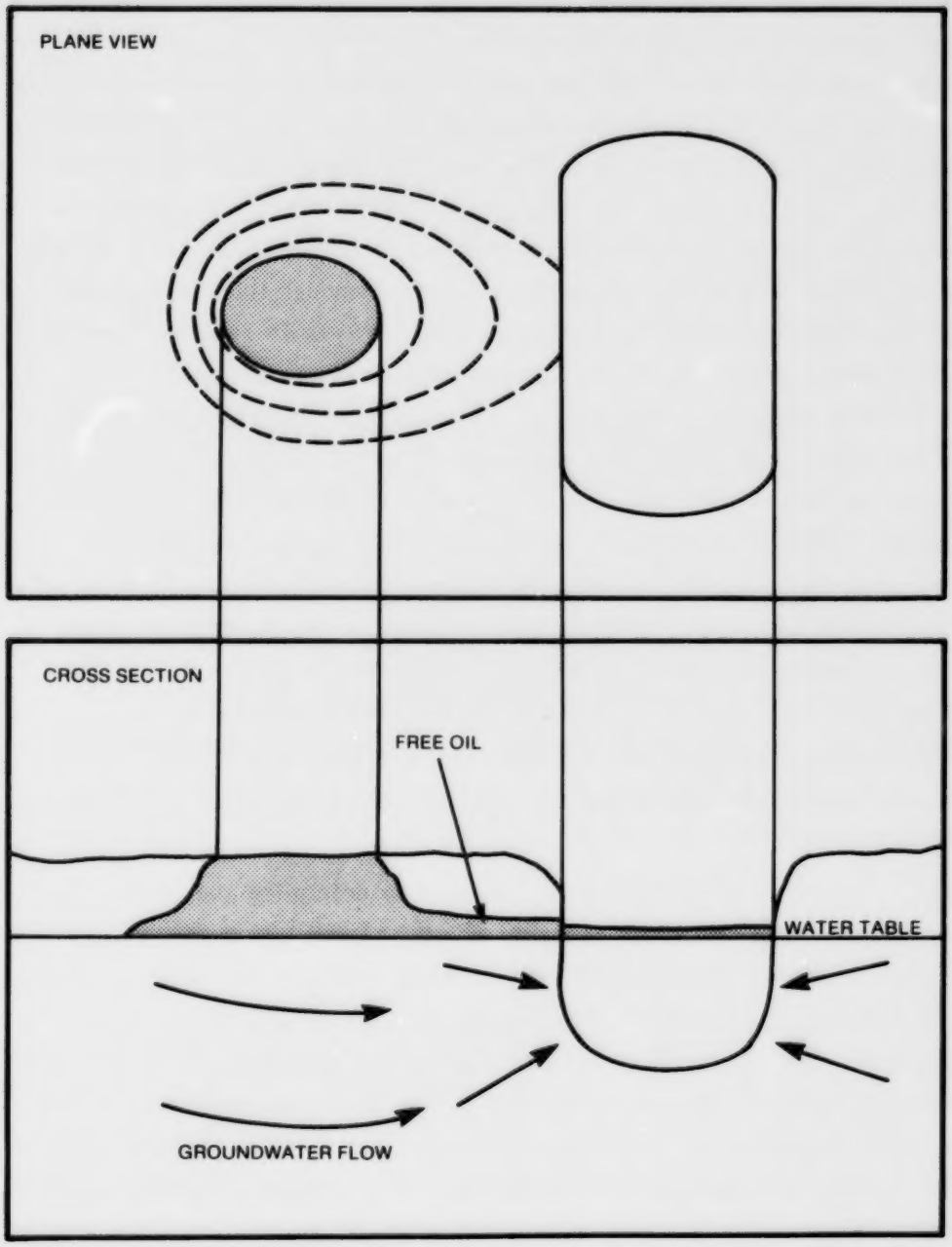

FIGURE 2 INTERCEPTION OF SPILL BY TRENCH CONSTRUCTED ACROSS MIGRATION PATH (23)

removal, continuous oil recovery is usually sufficient to prevent oil from entering the ground beyond because the higher level of the surrounding capillary fringe (earth saturated with water) acts as a barrier to the oil (23).

Unless the product removal system requires that the trench be open, a string of perforated culvert pipe is laid along the bottom and then the trench is backfilled with broken rock or gravel. Sumps are left along the length of the ditch for oil and water removal (Figure 3).

There are two main types of trench recovery systems. The first is an open trench where a skimmer is utilized for substance removal. Although this system produces virtually water-free oil, the rate of recovery is very slow as it depends on natural gradients to transport the oil to the trench. The second configuration uses a pump for substance removal from the trench, which may or may not be backfilled. This system is more effective for rapid recovery since a gradient is created towards the trench. The drawback to this method is that much larger volumes of water which may contain unacceptable concentrations of dissolved hydrocarbons must be disposed of (22).

There are several advantages in using the trench approach for recovery. The materials and equipment necessary to install the system are usually locally available. This method is uncomplicated and can be installed relatively quickly. The trench, however, must bisect the entire width of the spill making this technique only feasible for spills of limited extent. Also, the depth of the trench is limited and any skimmer or pumping equipment must operate continuously or the product will accumulate and migrate around the ends of the ditch (22).

Wells. Inspection or test wells can be used to determine the extent of the contaminated area, and subsequently as recovery points. Jetted or driven wells make good test points but their size limits their use in recovering contaminated water or oil.

Some well-drilling techniques were outlined in Table 7. The type chosen will be determined by the well diameter, depth and location. Although wells with diameters of 1 m or more have been used, diameters of 10 to 30 cm are more common. A large diameter well offers only a small advantage over a smaller well in its rate of fluid recovery — the main requirement is that the well be large enough to accommodate a suitable pumping arrangement (23). Once drilled, casing should be installed in the well to prevent it from caving in. Any tubular product with sufficient strength and resistance to the substance will do. Ease of handling, availability, and cost will also be considerations. The section of casing through which the water will enter the well should either be

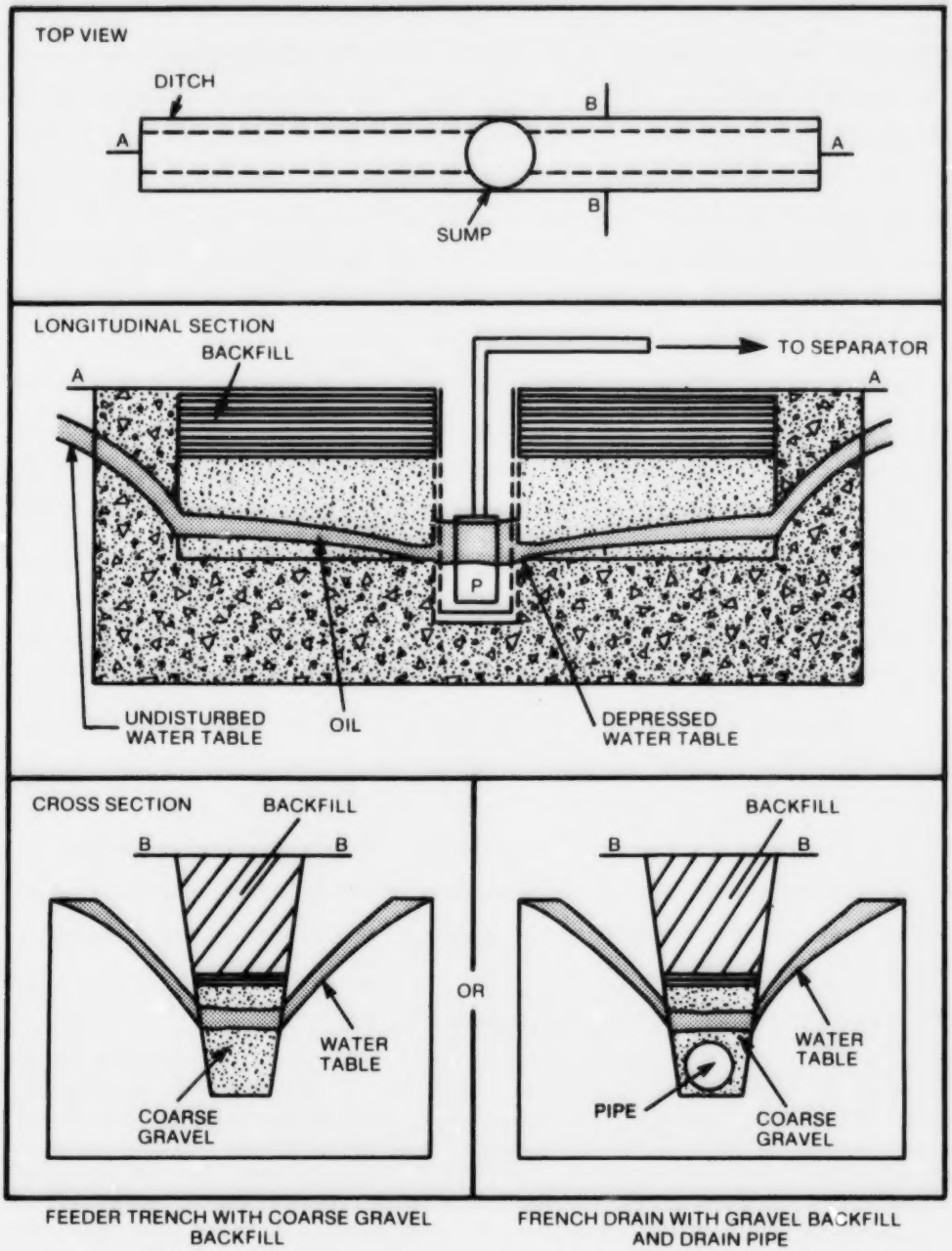

FIGURE 3 **RECOVERY DITCH WITH SUMP (23)**

perforated or slotted and covered with screen before it is installed. This section of pipe, called the screen, should extend both 1.5 m above and below the normal water level to accommodate fluctuations. The size and locations of the perforations will depend upon the soil characteristics and the gravel packing around the pipe. A continuous slot wire wrap screen will maximize the percentage of open area. This is desirable as the screen is easily clogged by bacterial growth, and the more open area initially provided, the longer the well can operate before maintenance is needed to clean and redevelop the well to restore its efficiency. A properly installed gravel-packed pipe will minimize the infiltration of fine sands or the need for additional screening. Figure 4 illustrates the proper installation of test and recovery wells (27).

An important consideration is the location of the wells themselves. The correct spacing between them will ensure adequate overlapping between their cones of depression (Figure 5). This can be determined by the superimposition of drawdown formula for single wells. Wells should not be operated outside of the spill area unless dictated by surface conditions. Although wells outside the spill area are sometimes used to trap the substance between the spill area and the natural water discharge point, using this technique will extend the zone of contamination. Problems can also arise where the groundwater layer is thin and particularly when an upper contaminated layer is separated from a lower uncontaminated layer by an aquiclude (a band of impermeable material such as clay). Not only will excessive deepening of the recovery well be unproductive in that case, but the perforation of the aquiclude could result in loss of oil recovery efficiency or contamination of the lower confined aquifer. Finally, care must be exercised in urban areas; excessive lowering of the water table may weaken the load-bearing properties of the soil and may cause settling of foundations. A floating level control mechanism can be fitted into the wells to ensure that water removal pumps operate within a limited range of groundwater fluctuations (23).

There are several types of recovery systems utilizing wells:

a. Single Pump System Using One Well (Figure 6). In single pump wells, oil and water are removed together through a single pipe and passed to an above-ground storage or treatment facility. The output of the pump is adjusted to maintain the required drawdown of the water table. One advantage to this system is its low cost. Since only one pump is required and complicated electronic controls are not needed to regulate the pumping levels (a single mechanical floatation device can be installed), it is cheaper to construct than other well configurations. Also, wells can be of smaller diameter, thus reducing costs for drilling, materials, and soil disposal. Moreover, a small diameter well recovery system needs less maintenance, is less unsightly, and can be installed and handled by one person.

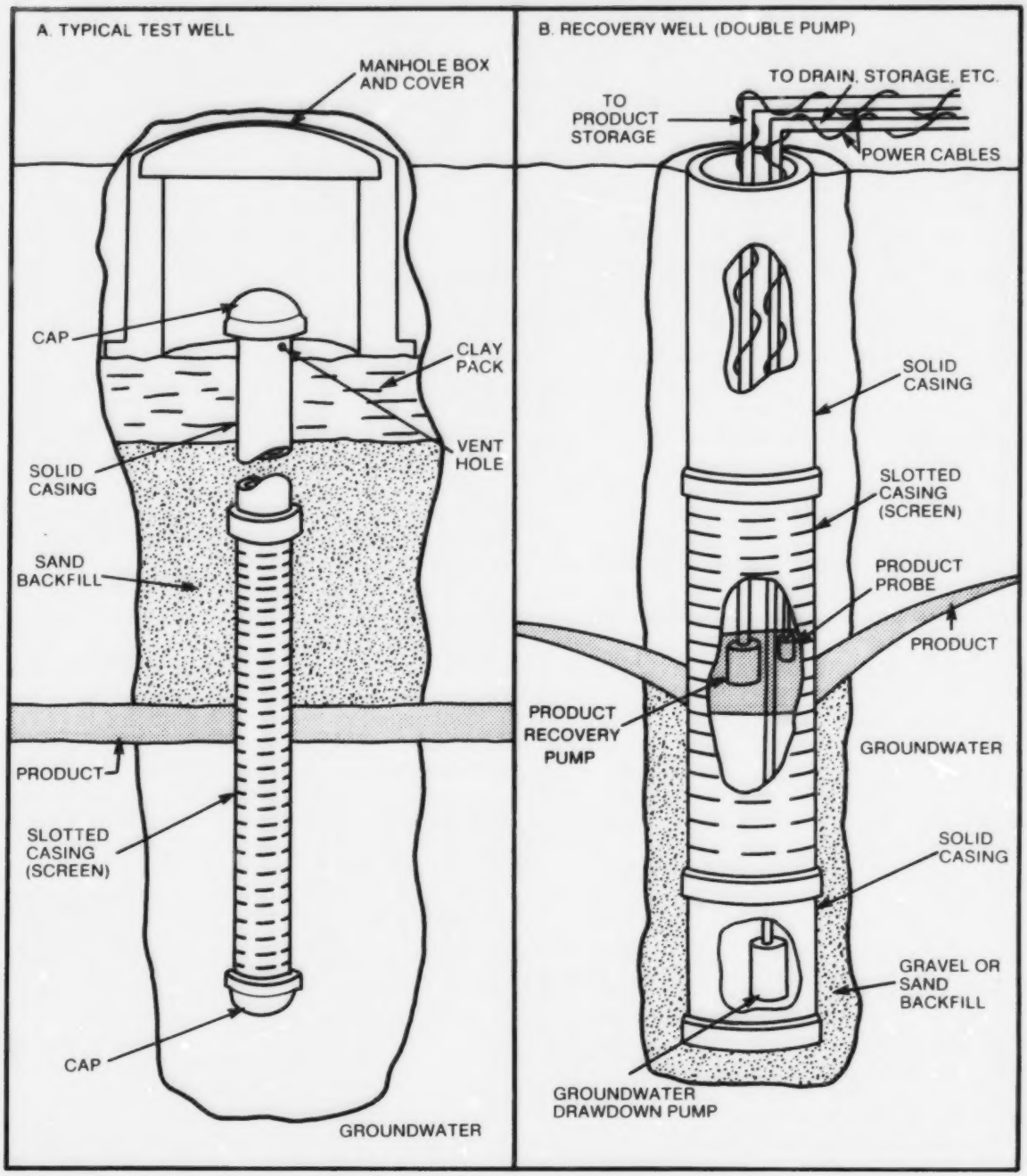

FIGURE 4 WELL CONSTRUCTION

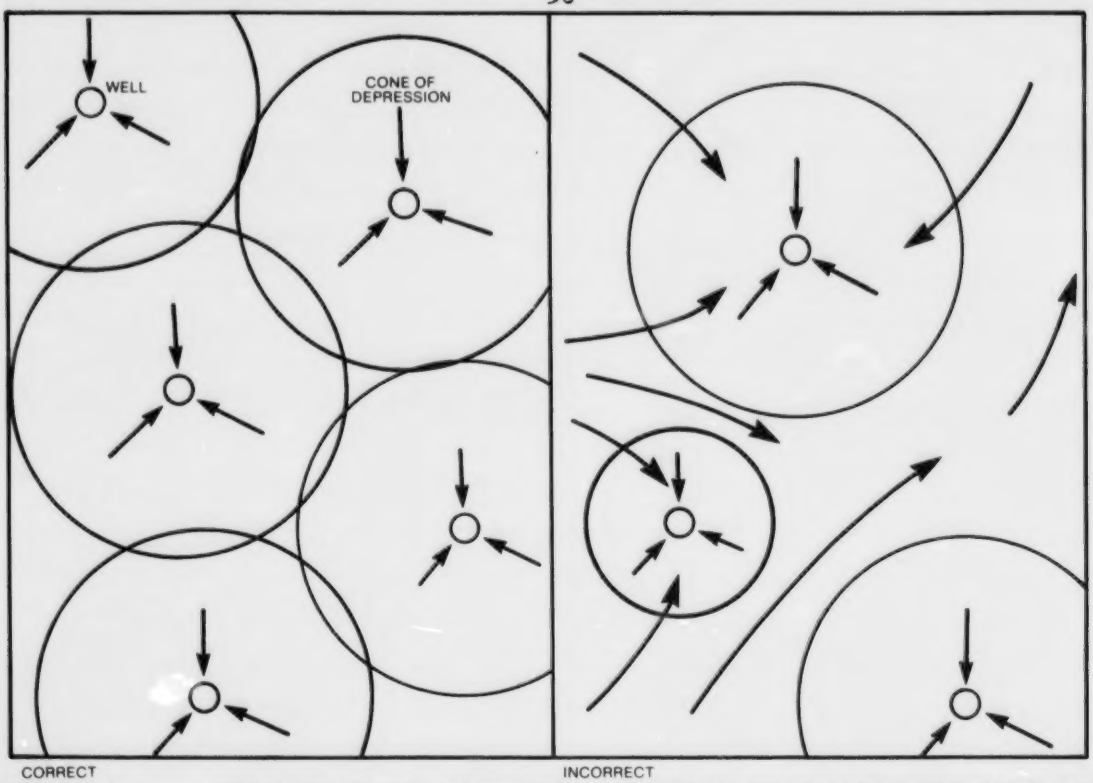

FIGURE 5 SPACING OF OIL RECOVERY POINTS IN CONTAMINATED ZONE (23)

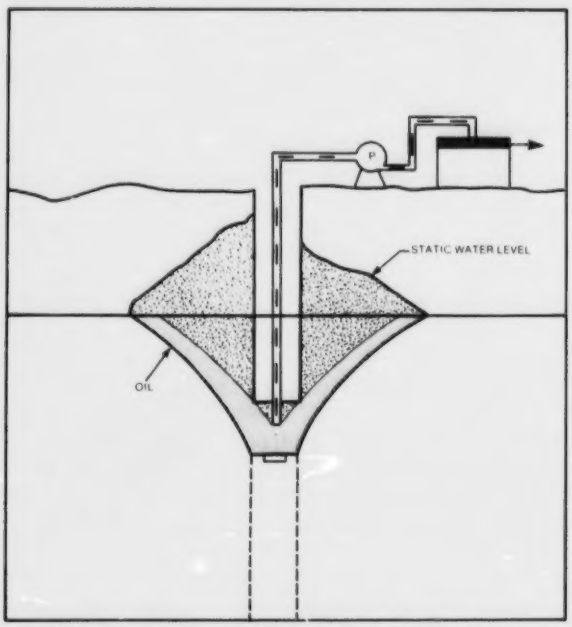

FIGURE 6 SINGLE PUMP RECOVERY SYSTEM (23)

One pump systems, however, require the use of separators to separate the substance from the water at the ground surface. Substance/water separation may be complicated by the agitation of the contaminated water during recovery. This may emulsify the substance and increase the amount of soluble hydrocarbon components retained in the wastewater (22). This can be alleviated somewhat by using displacement pumps such as piston pumps, Archimedean screw pumps and diaphragm pumps rather than the centrifugal type. Generally, it is most convenient to use a single-pump system where the oil/water recovery rates are relatively low (i.e., 2000 L/h or less), when it is expected that the recovery system will be in operation only for a short period of time, or when the use of a more complicated system is not justified by a cost/benefit analysis (23).

b. Single Pump System Using Multiple Wells. The same problems and advantages exist here as with single pump arrangements, but in ground formations of low permeability, this may be the only feasible recovery alternative (22).

c. Two Pump System Using One Well (Figure 7). This configuration is generally the most desirable arrangement. A water pump is installed with its intake near the bottom of the well and water is withdrawn at a controlled rate to create a cone of depression. A substance pump is suspended on a cable above the water pump and adjusted so that its intake is at or just below the oil/water interface. Automatic controls are attached to the substance pump to cause it to start up as the substance is accumulated and shut down if the pump intake is in water. The water pump has controls that cause it to stop if the substance accumulates in the well and approaches the level of the water pump intake (22).

There are several advantages to using this technique. Since the substance is separated from the water in the well, surface separators are not usually necessary. In fact, the substance can often be removed and sold without additional refining. The addition of soluble components to the wastewater is minimized and the system is fully automatic and can be operated continuously. This allows a more efficient and faster recovery. The disadvantages include the need for a larger diameter casing and screen (25 cm minimum) to house both pumps. The equipment is also more complex and more expensive, and the resistivity probes that are commonly used to detect the substance in the well and operate the substance pump require periodic maintenance and cleaning. Because it is more complicated, the equipment is subject to more frequent failure and malfunction (such as oil being pumped through the water pump or vice versa). This can be expensive and time consuming to repair. In addition, extreme care must be taken in the initial start-up and adjustment of the system to maintain the oil/water interface at a constant level. To this end, the well must be routinely monitored for several days following start-up to assure that pumping levels stabilize. However, when a large volume of oil is to be recovered, a double pump system is the most efficient (22).

d. Two Pump System Using Two Wells (Figure 8). This system can be used when a small diameter well that is incapable of housing two pumps is already in use. A second small diameter well can be installed nearby; it would hold the substance recovery pump which would be positioned higher in the aquifer than the existing well. Water removed from the original (lower) well would create a cone of depression, and accumulating substance would be removed from the other well. Care must be taken to ensure that the substance does not accumulate in the water well. Therefore, automatic controls should be installed to stop the water pump in this eventuality or if the product pump fails (22).

e. Pump and Skimmer System (Figure 9). This technique can use one of several types of skimmers depending on the diameter of the well. The main types are floating skimmers, sorbent belts, and sorbent ropes. The pump creates a cone of depression while the skimmer removes the product from the surface of the water in the well. Fabrics used

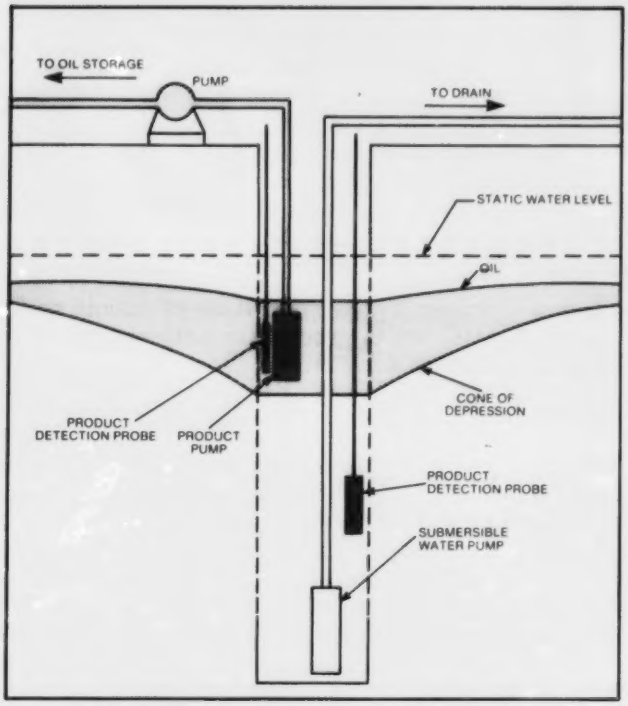

FIGURE 7 DOUBLE PUMP RECOVERY SYSTEM (23)

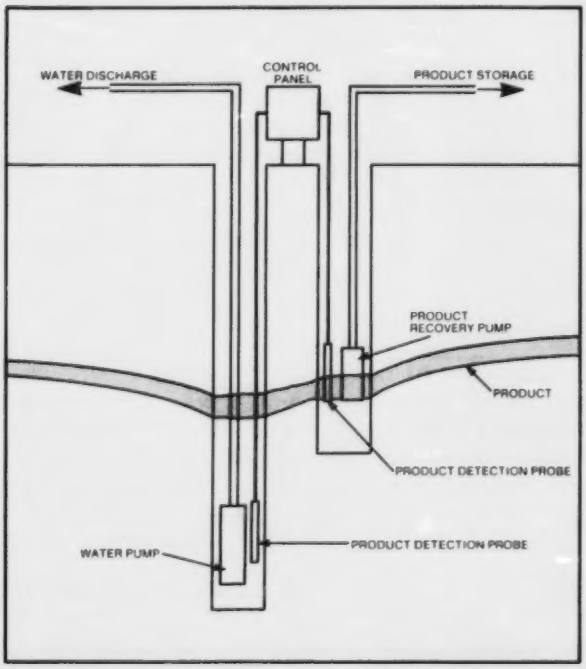

FIGURE 8 TWO PUMP SYSTEM USING TWO WELLS (22)

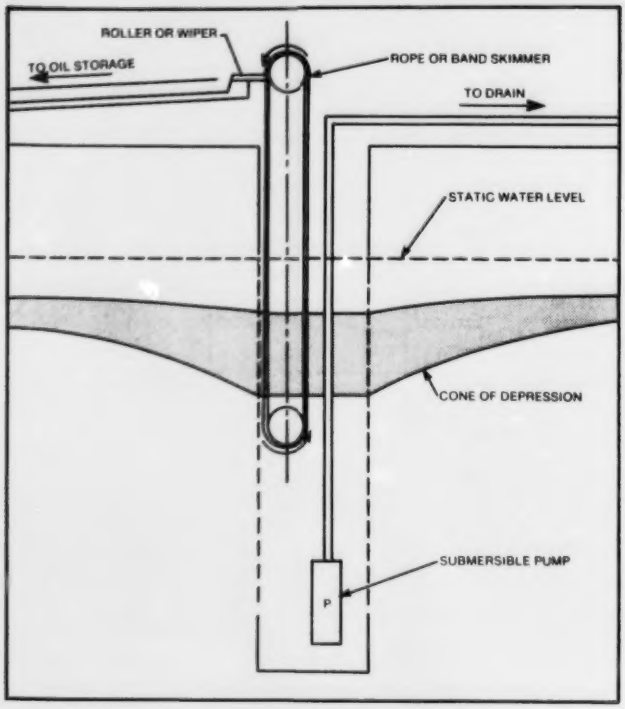

FIGURE 9 PUMP AND SKIMMER RECOVERY SYSTEM (23)

as belt material will have limited lives and must be periodically replaced; steel is a more durable material. The oil clings to the oleophilic steel band while the water is repelled, hence virtually water-free oil can be recovered. This system can be fully automatic, for intermittent or continuous operation. This method, however, is best suited to recoveries involving smaller amounts of product (23), that is, when the oil layer cannot be efficiently removed by simple double pump systems.

f. Double Shaft Well (Figure 10). The inner shaft of a double shaft well prevents oil from being drawn into the water recovery pump. This type of well can be shallower than double pump or pump and skimmer wells, but the diameter of the outer casing must be larger. For this reason, the well becomes uneconomical at depths exceeding 6 to 8 m. One advantage is that the pollutant may be recovered by either pump or skimmer (23).

g. Combined Well and Collecting Chambers (Figure 11). This system combines a recovery well with a second shaft that has both separation and collection chambers. The recovery well is fitted with a pump system that leads into the second shaft. The method, however, is expensive and is only justified for long-term recovery, recoveries involving large amounts of product or, since all the equipment is underground, in areas where the visual impact of above-ground equipment is unacceptable (23).

Recovery crock (Figure 12). The recovery crock is used in areas where there is little or no groundwater movement or where the groundwater is contained by some artificial barrier and is less than about 4 m from the ground surface. Concrete cylinders

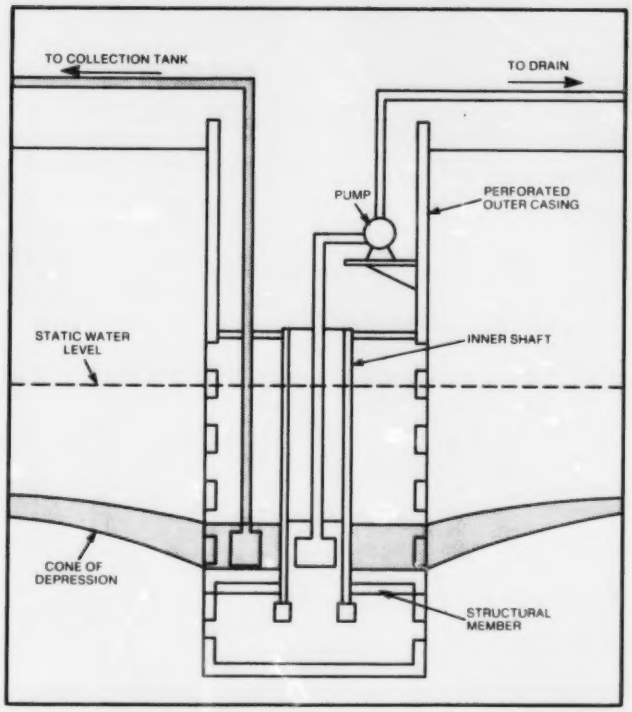

FIGURE 10 DOUBLE SHAFT WELL (23)

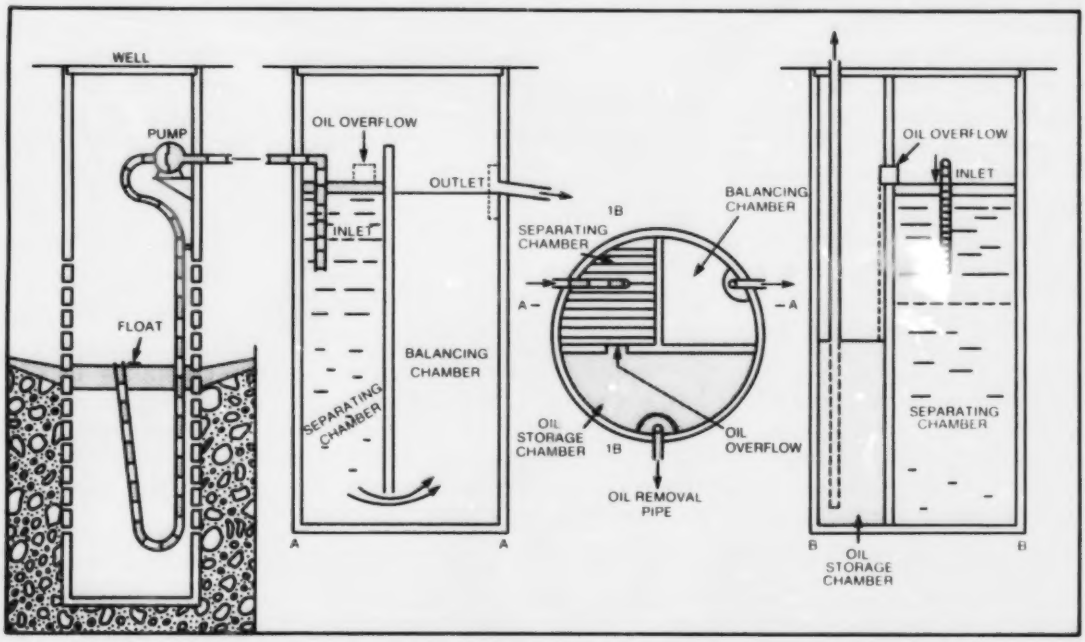

FIGURE 11 COMBINED WELL AND COLLECTING CHAMBERS (23)

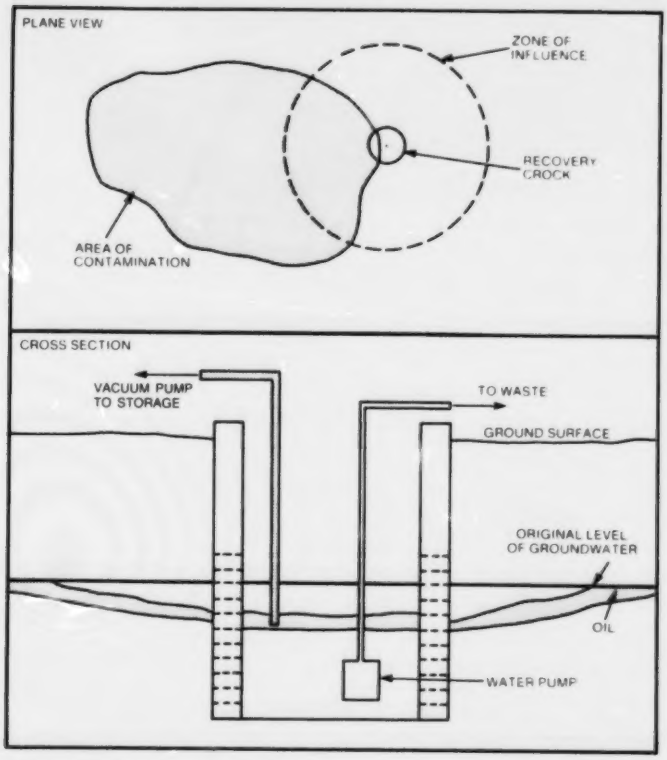

FIGURE 12 RECOVERY CROCK (12)

approximately 122 cm in diameter with 6 cm diameter holes cast into their walls that are commonly used in dry well construction, are placed in the ground just downstream of the area of heaviest contamination. The area surrounding the dry well is backfilled with gravel (stones of 2.5 to 5.0 cm diameter). A float-activated submersible pump is then used to lower the groundwater level while a second pump or vacuum truck removes the product that migrates into each "crock". This system has relatively low installation costs and can be constructed with readily available materials. Long-term maintenance and operation, however, is expensive and some automatic control is needed to prevent the water pump from pumping the contaminant.

A variation of this system uses a barrier curtain constructed of an impermeable material such as a bentonite-cement slurry. The barrier deflects the oil to a recovery crock (Figure 13). This method can be used on stream banks to intercept oil that would otherwise seep into the stream (12).

Equipment. Some of the commercial systems frequently used for oil recovery in groundwater and operating on the double pump principle are outlined briefly in Table 10 (28).

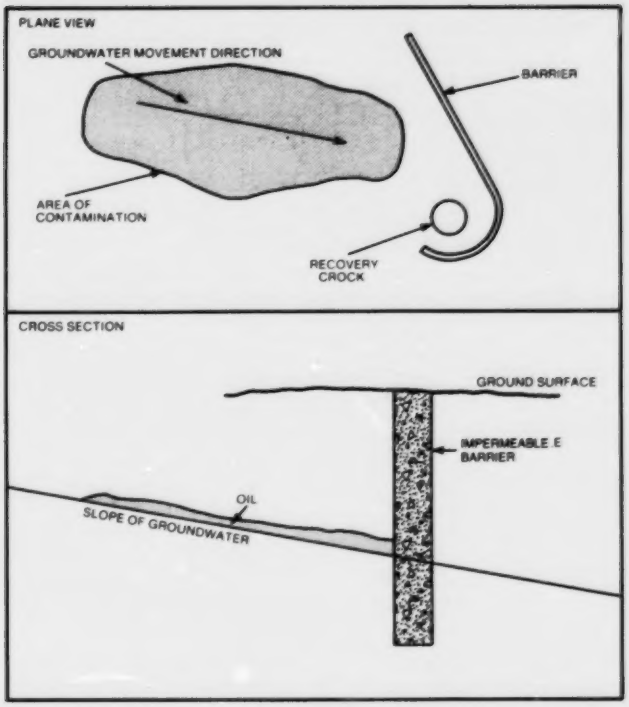

FIGURE 13 RECOVERY CROCK WITH DEFLECTING BARRIER (12)

4.2.2 Groundwater Treatment.

Carbon adsorption. Carbon adsorption (CA) is a commonly used means of purifying contaminated water. Many compounds in solution can affix themselves via attractive forces to the solid surface of activated carbon until equilibrium is established with the concentration in solution. The carbon is produced from materials such as wood, coal, peat or lignin which are dehydrated and carbonized (i.e., burned at high heat in the absence of oxygen). Pore openings in the carbon are then enlarged by activation to increase surface area of each carbon particle which increases the overall adsorptive capacity.

This method depends on the molecular size, structure, solubility and polarity of the molecule being adsorbed, as well as the type of carbon, the pH of the solution and the carbon contact time. The rate of adsorption is a function of temperature and concentration. Treatment involves passing the contaminated solution through carbon columns or beds, usually at the site. The carbon's effectiveness should be periodically tested during the course of the treatment, because the capability of the carbon to remove the substance will become exhausted after a period of treatment. This point is known as

TABLE 10 GROUNDWATER AND PRODUCT RECOVERY EQUIPMENT (28)

1. **Petropurge-Hydropurge (NEPCCO)**

Type: Double Pump

Description: The petropurge pump distinguishes between hydrocarbons and groundwater by means of a probe (measures the thickness of the oil layer and turns the pump on when the oil accumulates to a predetermined thickness).

The hydropurge groundwater drawdown pump is water-specific and is controlled by a probe which senses the oil/water interface.

Remarks:
- Cost of a system is approximately $20 000, but with accessories (e.g., a vapour extraction unit) and installation it can cost as much as $50 000 ($CAN).
- Capable of handling large volumes over long periods of time.
- 98% separation of hydrocarbon is claimed.
- Uses a small diameter well (15 to 20 cm).
- Recovery of 3500 to 4500 L/week of product is claimed.

Manufacturer: NEPCCO, Equipment Division

Distributor: Sanivan Inc.

2. **Scavenger (Oil Recovery Systems)**

Type: Double Pump

Description: The components include a filter-scavenger (a filter cartridge mounted in a floating collection unit that allows hydrocarbons to pass but rejects water) or a probe-scavenger (a separator for confined spaces; pump is controlled by a probe that differentiates between water and hydrocarbons) and a submersible water depression probe-pump (pump with probe that turns pump off when hydrocarbons approach its intake).

Remarks:
- Probe scavenger can operate in wells in 10 cm or greater.
- Price for system varies between $9000 and $12 000 ($CAN).
- Filter-scavenger; maximum recovery rate: 18 L/min; minimum well diameter: 61 cm
- Probe-scavenger; maximum recovery rate: 144 L/min; minimum well diameter: 21 cm
- Recovered product is claimed to be virtually water-free.

Manufacturer: Oil Recovery Systems Inc.

Distributor: RNG Equipment

3. **SOS Skimming System**

Type: Double Pump (Air-Driven)

Description: The system is composed of: a water drawdown pump, a specific gravity skimmer or an oil permeable membrane device skimming to 0.5 mm as reported and a product recovery pump. A pneumatic control system is used to regulate the pump rates according to the groundwater flow fluctuations and the recovery tank level.

Remarks:
- Several specific gravity skimmers can be attached together for large volume spills.
- The SOS (Selective Oil Skimming) system can be installed in a 10 cm ID well and the specific gravity skimmers in a 5 cm ID well. Both systems can be used in a shallow well (0 to 5 m) or a deep well (to 60 m). In a deep well a tandem pump operates above the skimming system.
- Costs for the selective oil skimming system and the specific gravity skimmers are approximately $5000 and $8000 for shallow well and $6000 and $10 000 ($U.S.) for deep wells. Some parts of the components can easily be replaced by Canadian ones thus reducing the costs for Canadian buyers.
- Specific gravity skimmers in a 5 cm well claimed to recover 110 L/h of products with a 20 L/min water drawdown.
- The deep well pump in a 5 cm well operates at: Fuel - 1.0 L/min, Water - 6.0 L/min Higher rates should be obtained in larger well size.

Distributor: Clean Environment Engineers

the 'breakthrough' point. The spent carbon must then be replaced or regenerated for reuse; thermal regeneration can often be conducted in the field with the proper equipment.

There are several considerations that should be kept in mind when using this method to treat contaminated groundwater. The carbon must be ordered for use in the field. Wetting the carbon prior to use results in more efficient adsorption; this may take 1 to 2 days and it requires clean water. It is also necessary to prepare curves that predict the onset of 'breakthrough' so that operators know when to replace the carbon and/or use other columns. The use of carbon columns simply as filters is an inefficient use of activated carbon's adsorptive capacities. For this reason, clarification (or filtration) prior to carbon adsorption is usually a necessary pretreatment step. Finally, bed stratification (layers within the carbon bed at which different compounds can be adsorbed), good flow distribution, and an underdrain system to prevent the carbon from exiting with the effluent will all increase the efficiency of the system. Properly used, it is not uncommon to remove 95 to 100 % of the contaminants associated with hydrocarbons (such as xylene, toluene or benzene) present in the ppb and low ppm range. Carbon adsorption is also used as a polishing process for other water treatment methods dealing with higher contaminant concentrations. Environment Canada's Environmental Emergency Technology Division evaluated an adsorption treatment system (29) that treated the concentrated stream of a reverse osmosis (RO) water treatment process. In those tests, the RO unit concentrated the contaminated water, reducing its volume to only 10% of the original amount. The concentrated water was then treated with activated carbon; adsorption greater than 95% was achieved for benzene, toluene, 1,1,1-trichloroethane, and trichloroethene once the feed-water was concentrated with RO from 0.1 to 1 ppm to 1 to 10 ppm. Xylene, ethylbenzene, toluene, benzene, and hexane from a petrochemical drainage lagoon effluent were removed at 95 to 100% once concentrated to 3.86 ppm, 0.54 ppm, 0.19 ppm, 2.6 ppm, 0.57 ppm, respectively, twice their level in the lagoon effluent.

The following are some examples of available carbon adsorption equipment for hazardous wastes:

Oil Recovery Systems Inc. (ORS) (28)

Distributors:	RNG Equipment
Equipment:	Activated Carbon Adsorber Water Purification System
Remarks:	- Available in 760 L (38L/min) and 3780 L (189 L/min) units requiring 270 kg and 1360 kg carbon respectively.

- It is able to remove benzene, toluene, xylene and PCBs from water. (Developed originally to handle gasoline and PCB-contaminated water.)
- It can be combined with ORS's air stripper or coalescer for more complete water purification.

Calgon Canada (28)

Equipment: Gravity Flow Carbon Adsorption

Remarks:

- The unit is trailer mounted and single or multiple pre-piped adsorber vessels are available.
- The vessel contains about 10 tons of granular activated carbon (2 grades are available - Filtrasorb 300 and 400).
- It will remove dyes, phenolics, pesticides, PCBs, aromatics, esters, ethers, ketones, non-polar compounds with more than four carbon atoms and refractory organic compounds not responsive to biological treatment in high or low concentrations.

Air stripping. In air stripping (28), contaminated water is cascaded down through a column counter-current to a high flow of air from a blower at the bottom. The column contains a packing material that is used to increase the area of contact between the water and air. The contaminants are "stripped" from the water and leave the tower with the air. Obviously, highly volatile compounds such as light hydrocarbons are more easily removed. The efficiency of this method depends on the packing type, the height and diameter of the column, and the air-to-water ratio. When the water flow is too high, there is less contaminant removed; on the other hand, an excessive air flow will cause increased costs and may cause the water to run down the sides of the tower instead of over the packing, a phenomenon known as channelling. Removal of immiscible products from the feed water is necessary to prevent fouling of the tower packing.

The induced air stripper is a variation of air stripping, in which contaminated water is sprayed through nozzles that induce large amounts of air to enter concurrent with the feed. The water droplets fall to the bottom of the unit while the volatile contaminants go into the vapour state and are vented. This technique is cheaper than the packed tower method, but only 60 to 85% of volatile organic components (compared with 70 to 90% for a tower) are removed. Whether using a tower or nozzles, air stripping is usually an inadequate means of removing contaminants for drinking water purposes, and is generally used in combination with another method of treatment.

Off-gases from this treatment process must meet air quality standards: the gas effluent requires a treatment in most situations. Air stripping without contaminant recovery is now being banned in several jurisdictions in the United States. Environment

Canada's Wastewater Technology Centre evaluated the efficiency of air stripping for the removal of volatile organics from contaminated groundwater (30). Different packing size and type were used in a PVC column 180 cm high, 15 cm in diameter and the air-to-water ratio was varied from 70:1 to 110:1. Benzene and toluene present at 107 ppb and 49 ppb were removed by more than 99% using a liquid flow rate of 4 L/min, an air:water ratio of 70:1 and a packing of Intalox saddles measuring 1.3 cm. The off-gases were treated using activated carbon in two adsorbers positioned in series, which reduced the concentration of all the components from 1 to 40 ppb in the influent to below the limit of detection of 2 ppb in the effluent. Mass transfer coefficients and granular activated carbon loading at saturation were compared to predicted values.

An earlier study from Environment Canada's Wastewater Technology Centre demonstrated that air stripping concentrated groundwater micropollutants (in the low ppm range) using reverse osmosis does not influence the removal efficiency. The influence in the removal efficiency of the off-gases treatment system is still to be determined.

The following are some examples of available air stripping equipment for hazardous wastes:

Oil Recovery Systems Inc. (28)

Equipment: Air Stripping Water Purification System

Remarks:
- There are four sizes, ranging from 95 to 454 L/min to 1703 to 3785 L/min units.
- Units are made of fiberglass reinforced plastic.
- Units include high-low water probes and a mist eliminator.
- Options include automatic controls, stainless steel construction, winterization (heat tape, insulation).

NEPCCO, Equipment Division

Equipment: Airpurge Systems

Remarks:
- Continuous, fully automatic equipment that can be built to order.

Calgon Canada

Equipment: Interphase System - Airstripper and Airstrip Computer Program

Remarks:
- The computer program evaluates the efficiency of AS (instead of an on-site pilot study) given the total number of compounds to be stripped, influent concentration of each, influent flow rate and treatment objectives.
- The program should give the optimum design, cost/benefit ratio for removals at higher levels of contamination.

Steam stripping. Steam stripping involves passing steam through a liquid with sufficient contact that the volatiles are transferred from the liquid to the gas phase. This process is efficient for the recovery of volatile and immiscible substances such as gasoline, diesel fuel, solvents.

Steam is introduced at the base of the stripping tower, which is filled with packing or fitted with trays to enhance contact between the two phases, and the liquid feed is introduced at or near the top. The steam leaving the top of the tower contains the volatiles. It is condensed and the insoluble products are recovered in a decanter.

The boiling point of the organics to be separated from the aqueous phase is the main indicator of the applicability of the process. The Henry's Law constants describing the extractability and volatility of the compounds as well as their solubility have also to be considered. Organics that have a relatively low boiling point (<150°C), a Henry's Law constant (~10^{-3} to 10^{-4} atm·m^3/mole), and a low solubility (<1000 ppm) are considered good candidates for steam stripping (32). Good candidates among hydrocarbons are benzene, toluene, and hexane (33).

The advantages of steam stripping over air stripping are possible concentration and recovery of contaminants and reduction of air emission of volatile organics. In some cases, steam stripping can be used to concentrate volatile organics sufficiently to yield a product that will support its own combustion. While air stripping is cost efficient for streams with less than 1% solvent content, steam stripping is used effectively for the removal of volatiles in aqueous solutions up to 10% solvent content. High removal efficiencies can be reached with air stripping; therefore, it can be used as a polishing treatment for the steam stripping treated stream. For further concentration of the steam stripping overhead, solvent extraction can be used (32).

Pre-treatment of the feed is necessary to avoid fouling of the tower packing with immiscible products.

Reverse osmosis. To properly understand reverse osmosis (RO), one must first understand the concept of osmosis itself. Osmosis involves the movement of solvent through a semipermeable membrane from a solution with low solute concentration to one with high solute concentration. The movement is caused by concentration gradients and stops when the solute concentrations are equalized on each side of the membrane. With RO, pressure is applied to the more concentrated solution, reversing the natural flow of the solvent. Generally, the applied pressure must be in the range 2068 to 6895 kPa (300 to 1000 psi) to overcome the osmotic pressure of the solution: the solvent (usually water)

flows through the membrane while the solutes are rejected. This is not a separation based on the size of the solute molecules; the type and amount of components removed depends on the chemical structure of the membrane, the chemical and physical nature of the component(s) and of the solution as well as the porous nature of the membrane and the recirculation conditions. The membranes themselves are commonly formulated from cellulose acetate or thin film composites (polymers) and are usually found in spiral wound, hollow fibre or tubular configurations.

The advantages to this method include: no phase changes, the technique works equally well for liquids and gases, and it has a lower energy consumption than most other separation processes. The feed water, however, must often be pretreated to prevent clogging of the membranes due to suspended solids, bacterial growth on the membranes, calcium carbonate or silica buildup, and hydrolysis from acidic or alkali water. Appropriate prefiltration will remove suspended solids and addition of sodium hexametaphosphate to the feed can be used to kill bacteria. Acidification of the feed will remove calcium carbonate (34).

Environment Canada's Environmental Emergencies Technology Division evaluated the efficiency of reverse osmosis on hydrocarbons containing leachates using a mobile unit (34,35).

At the Gloucester landfill site (Ontario) in the 1984 testing, a 97% removal efficiency was achieved for benzene using a polyether-polysulphone type of membrane. The benzene concentration in the groundwater was reduced to less than 4 ppb from a concentration of 70 to 120 ppb. In 1986, a more concentrated portion of the plume was used for further testing. Benzene and toluene concentrations were reduced from 1530 ppb and 280 ppb to 55 and 10 ppb using the same type of membrane and recirculation ratio. A removal efficiency of 96% for both contaminants was obtained.

At the Toronto Shell site, the leachate containing toluene (0.09 ppm), xylenes (2.79 ppm), benzene (1.31 ppm), hexane (0.30 ppm) and ethylbenzene (0.23 ppm), was also successfully treated with polyether-polysulphone reverse osmosis membranes. The concentrations and removal efficiencies achieved were: toluene (0.02 ppm, 78%), xylenes (0.4 ppm, 86%), benzene (0.43 ppm, 67%), hexane (0.01 ppm, 97%) and ethylbenzene (0.03 ppm, 87%).

Examples of some equipment available for collection of hazardous wastes:

Environmental Emergencies Technology Division, Environment Canada

Equipment: Mobile UF/RO Unit

Remarks:
- The unit is available to demonstrate the efficiency of the technique on hazardous solution wastes not already tested as well as for environmental emergencies purposes.
- The unit is trailer mounted, helicopter portable, and is self-contained with diesel powered pumps.
- Can produce up to 1800 L/h pure water from salt water and can contain up to 12 RO or ultrafiltration (UF) membranes.
- Contains fuel for eight hours of continuous operation and has a built-in propane heater to prevent freezing during cold weather operations.
- The unit automatically shuts down if normal operating pressures and temperatures are not maintained, if an outlet is blocked or if a membrane ruptures.
- Efficient for some organics and inorganics in aqueous solutions in the pH range of 2 to 11 (PCB (36), PCP (37), volatile organics (29), pesticides (38), oily wastewater (39).

Company: Memcare Inc.

Company: Seagold

Company: Seprotech Systems Inc.

Company: Zenon Environmental Inc.

Ultrafiltration. Ultrafiltration (UF) is a pressure-driven separation process which can concentrate dilute products or recover certain chemicals while operating at lower pressures than reverse osmosis (28). Better separation will be achieved with large molecular weight substances as this method is based on molecule size. Ultrafiltration membranes have pores in the range of 10^{-8} to 10^{-2} µm and operate at 0.18 to 1.1 MPa while other media (such as cloth or metal screens) can separate particles only as small as 1 µm. The separation characteristics of UF are determined by the media porosity and thickness as well as system variables (e.g., pressure, temperature, feed velocity and waste composition). A significant advantage with UF is that it uses lower operating pressure than reverse osmosis. This is because the UF media are microporous; the osmotic pressure of the materials retained by them is so low that it does not significantly influence the solvent flux. It is much slower than high-pressure processes such as reverse osmosis; however, UF can be sometimes interchanged with RO, using the same basic hardware packaged to increase the versatility of the treatment capability. Ultrafiltration membranes can be obtained in the same configuration as used in RO, i.e., tubular, spiral wound or hollow fibre, and are commonly made from cellulose acetate or inorganics such as zirconium oxide. They can be custom manufactured with different pore sizes for the separation of specific molecular weights between 500 and 200 000 g/mole (Osmonics, The

Filtration Spectrum, 1984) but the solute molecules should be at least one to two orders of magnitude larger than the solvent molecules. Membrane fouling and degradation are similar to that of RO, but usually to a lesser extent. As well, wastes containing high levels of low molecular weight compounds may require additional treatment for the effluent.

Examples of some equipment available for collection of hazardous wastes:

Environmental Emergencies Technology Division, Environment Canada

Equipment: Mobile UF/RO Unit

Remarks: - See section on Steam stripping

Romicon Inc. - Subsidiary of Rohm & Haas Company

Equipment: Hollow Fiber UF System

Remarks:
- Used in a variety of chemical process industries, it can purify oil-contaminated water.
- The system consists of hollow fibre cartridges, permeate storage tank, circulation and backwash pumps.
- The feed is pumped under pressure through inside of fibres; separation occurs at the liquid/membrane interface with rejected solutes and particles remaining inside skin and permeate flowing through the hollow filters.
- The flow along the hollow fibres can be controlled to produce high shear forces to break away particles and force them downstream.
- Cartridges are cleaned by flushing, recycling, back-flushing or by a combination of the three.
- Works in temperature range 15 to 75°C and pH range 1.5 to 13.0.
- Capacities vary from 2.8 to 5.6 m^3/d up to 70.9 to 141.9 m^3/d.

Gravity separation. Often, during emergency recovery operations, a single submersible or suction pump that recovers both groundwater and floating product is installed. A simple means of processing the oil/water mixture produced by this method is gravity separation. The recovered mixture is allowed to stand so that the immiscible oil and water form two distinct layers (Figure 14). This system is easy and inexpensive to construct and can usually be placed in operation in a matter of a few hours. This method, however, cannot remove soluble components dissolved in the water and should be combined with some other separation process capable of doing so.

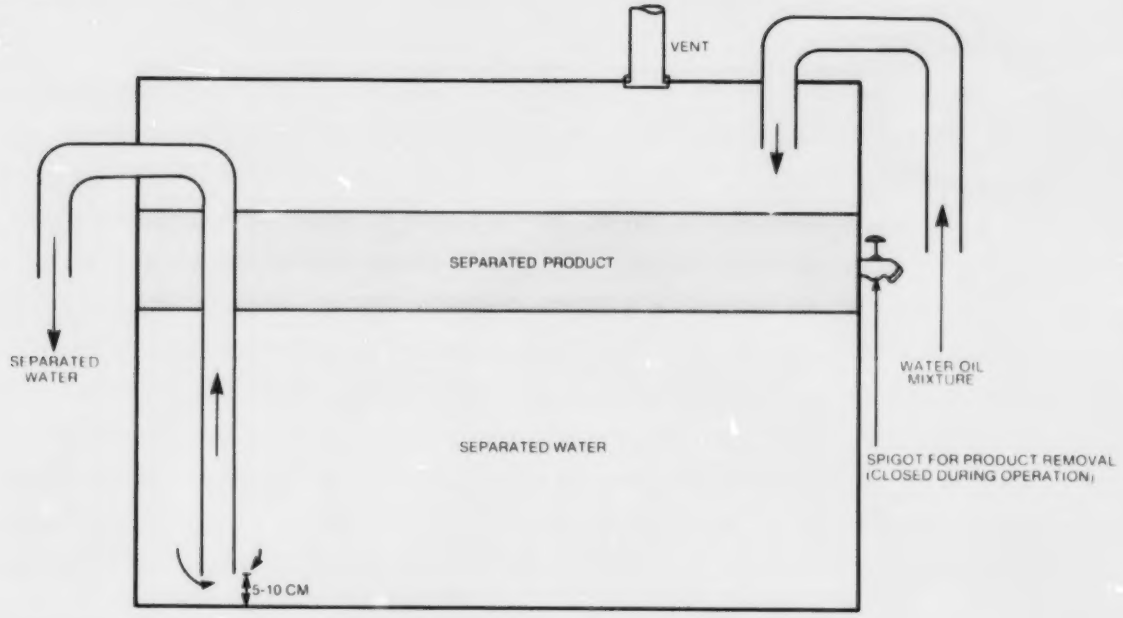

FIGURE 14 GRAVITY SEPARATION

Recharge. A means of accelerating cleanup and disposing of treated water is by recharging it back into the aquifer. Recharge also serves to wash some of the residual hydrocarbons from the soil and can be especially attractive for large-scale recoveries. There are several advantages to this technique. By using recharge wells to increase the hydraulic slopes of the groundwater, the number of recovery wells needed can be reduced. The recharge wells will cause stabilization of the hydraulic gradients towards the pumping wells, thus enhancing recovery rates and reducing long-term operating costs. Moreover, large volumes of water can be handled over an indefinite period (26).

The success of this technique depends upon proper design, operation and maintenance. It is sometimes necessary to treat the produced water prior to recharge (open system). This will be determined by the quality of the produced water and the method of recovery. Before any treatment is undertaken a cost analysis should be conducted. For example, with water requiring extensive treatment, capital and long-term maintenance costs of treatment could exceed those of well development and replacement, especially for shallow (<15 m) aquifers where well construction costs are

low. As well, treating the water to remove the dissolved components prior to recharge could be costly especially if there are a large amount of hydrocarbons in the soil. In the latter case, treatment would be particularly unrewarding as residual hydrocarbons would continue to infiltrate the groundwater for decades (26).

There are several other considerations to be made before undertaking treatment. The treated water may no longer be compatible with the aquifer water and may cause reaction and/or precipitation in it. Recharging problems can also occur due to treatment as in the aeration of the water. For example, in water with high iron levels, aeration may result in the precipitation of iron hydroxide and enhanced aerobic bacteria growth, both of which can severely plug recharge wells. Filter systems also provide a good medium for bacterial growth and must be monitored, cleaned and disinfected routinely. Algae is not usually a problem, unless the produced water is aerated and allowed to stand in the sun for an extended period as in settling basins. Quality control of the treated water and interference with its hydrocarbon washing properties should be verified prior to recharging (26).

According to Blake and Fryberger (26), it is more cost effective to simply recharge the water produced from the recovery well directly into the aquifer. The system is completely closed and can be designed so that the water is never exposed to air. It is crucial that the system be properly designed, especially with respect to placement of wells, or increased costs and the inability to contain the spill will result. Difficulties associated with direct recharge systems also include plugging (from suspended particles, air bubbles, chemical precipitations, emulsification and bacterial growths), formation reactions, and the accidental discharge of hydrocarbons through the water pump. The latter will require that some type of alarm system be installed that will cause the pump to shut off if hydrocarbons are detected. A closed recharge system has the advantage of being inexpensive and extremely flexible; each recovery well and associated recharge well(s) can be treated as a self-contained system (26).

4.2.3 Contaminated Soil Recovery. The only way of recovering contaminated soil is by excavation. Before this is undertaken, information on the water table level and soil geology as well as the depth of oil penetration must be gathered as excavation will not always be feasible, especially if large volumes of soil are involved. Generally, soil should only be removed in order to protect groundwater, or when the hydrocarbon-saturated earth presents a health hazard and the decontamination must be done quickly. Excavation is often prevented by local conditions, however, and extreme caution must be taken in

built-up areas to avoid damaging underground pipes and cables, foundations of nearby buildings, and to not disturb the stability of slopes (e.g., road and railway embankments, canal dams).

If soil must be removed, some type of support such as sheet piling should be used to prevent caving. Also, since volatile products present explosion hazards and/or may produce suffocating mixtures, explosimeter tests must be conducted before work commences and while the work is in progress. Self-contained breathing apparatus must be used when air quality is unsafe.

Care must be taken that excavations do not break through natural impermeable layers in the subsoil (such as clay layers) as this may cause the spill to penetrate deeper into the ground. As well, any excavation should be made as soon as possible after a spill has occurred in order to minimize the amount of soil that must be removed. Obviously, this is often not possible with slow-leaking underground tanks as leaks can go undetected for years and affect a wide area before response actions actually begin. Finally, CONCAWE (23) recommends that excavation only be done on the basis of visible and obvious oil contamination. It is not justified to remove quantities of oil that can be detected by odour alone. Removing large amounts of contaminated soil is costly, and methods of in-situ treatment should be considered first unless a health hazard exists (23).

4.2.4 Soil Treatment.

Biological degradation. Biological degradation of hydrocarbons involves their decomposition by microorganisms to ultimately produce microbial cells, carbon dioxide and water. The types of microbes that attack hydrocarbons include bacteria, fungi, algae, actinomycetes and protozoa; all are commonly found in surface soils and waters. Bacteria are the main decomposers. They have the largest population and are the most biochemically active soil microorganisms (28). Their very small size enables them to reach the subsurface. In fact, aerobic bacteria have been found in permeable formations to depths of several thousand feet, although they have more limited activities at these depths because of low levels of oxygen and nutrients. Anaerobic bacteria can live on oxygen found in chemical compounds, but they degrade hydrocarbons very slowly compared with the aerobic types.

Hydrocarbon biodegradation varies according to chemical composition. The more biodegradable substances are straight-chain paraffinic hydrocarbons. Branched-chain paraffins and cycloparaffins decompose more slowly. Aromatics should decompose

faster than cycloalkanes (40), but nonhydrocarbon compounds (in particular those with high molecular weights) are decomposed slowly (27).

In order to consume hydrocarbons, microbes need three things: oxygen, nutrients, and moisture. The first is needed because the decomposition of oil by microbes is essentially an oxidative process. Oxygen can be provided using air, pure oxygen, hydrogen peroxide, or ozone. Also, rapid biodegradation of oil requires certain nutrients such as nitrogen (commonly in the form of ammonia or nitrate) and phosphorus (commonly in the form of phosphates). Other nutrients such as minerals are necessary in smaller amounts and are usually found in the soil in sufficient quantities.

Bacteria cannot grow in completely dry soil since water is required to transport dissolved food (in this case, the hydrocarbon) into bacterial cells. They grow best in moist, crumbly earth.

Degradation of hydrocarbons occurs rapidly under optimum conditions of aeration, moisture and nutrients, conditions that seldom exist in nature, but can be created artificially by blowing air and nutrients into the ground through wells (27,41). In addition to the nutritional needs, more rapid biodegradation should be achieved when the bacteria culture has been already acclimated to the destruction of hydrocarbons. There are commercially available products that consist of dried microbial or bacterial cultures. Soil and water already contain microbes capable of consuming hydrocarbons; therefore, supplying proper nutrition, aeration and moisture to stimulate their activity is usually adequate (27).

The total interfacial area between the hydrocarbons and soil, and hydrocarbons and water, is the most important factor in the rate of their biodegradation in the soil -- the greater the interfacial area, the higher their rate of degradation. Pockets of excess hydrocarbons can decrease the interfacial area, and so the hydrocarbons should be distributed in the contamination area by plowing or turning the soil and mixing the contaminated soil into clean soil and vice versa. The rate of degradation is highest near the surface of the contaminated earth, especially if the soil is turned and mixed for aeration and adequate nutrients and moisture are provided. The rate is slower deeper in the soil as aeration and nutrient supply decrease. The rate is lowest where the hydrocarbons spread over the water table causing reduced oxygen and nutrient supply and a marked increase in saturation of the soil by hydrocarbons. In this case, the hydrocarbons will eventually spread over the water table, increasing the interfacial area and making the soil more amenable to biodegradation (27).

In summary, there are two categories of biological restoration techniques: the stimulation of the activity of the native microbial population within the aquifer by providing optimum conditions of oxygen, nutrients and moisture (42,43,44); and the addition of microbes acclimated to growth on contaminants (42). Biodegradation is best used to treat residual amounts of hydrocarbons in the soil when it is no longer feasible to use conventional groundwater and soil treatment techniques.

The following are some examples of available equipment:

Polybac Corporation

Equipment: Polybac Mutant Bacterial Hydrocarbon Degrader (28)

Remarks:

- Consists of mutant, adapted micro-organisms and biochemical accelerators.
- There are three strains: Hydrobac, Phenobac and Petrobac for the degradation of specific types of organic chemicals: Hydrobac microbes degrade refinery/petrochemical waste waters or spills containing a large number of chemicals in small varying concentrations; Phenobac are active specifically against surfactants and synthetic detergents; Petrobac is used to degrade spills of refractory organic materials in soil or salt water.
- Bacteria are dehydrated; they are activated with water (1:10) to form a suspension.
- Degradation rate depends on the chemicals involved, temperature and other soil conditions.
- Polybac E (a biodegradable emulsifier) can be added to the degraders to increase the interfacial area of contact between micro-organisms and the contaminants.
- Nutrients (Polybac N) are also available.
- Optimum temperature range is 10 to 40°C.
- Bacteria must remain completely dry prior to use.

FMC Corporation, Specialty Chemicals Division (28)

Equipment: Aquifer Remediation Systems (ARS) Enhanced bioreclamation Program

Remarks:

- The company offers a three-phase program with Site Assessment, Process Design and Program Implementation.
- The first phase costs $5000 to $10 000 ($U.S., 1985) for petroleum sites and includes groundwater sampling, laboratory evaluation and a review of site information.
- The second phase costs $10 000 to $30 000 ($U.S., 1985) and evaluates applicability of an ARS Program which includes soil sampling and assessment.

- The third phase costs $50 000 to $150 000 ($U.S., 1985) and includes equipment installation and operation, monitoring and troubleshooting, and site closure.

Groundwater Technology Inc. (a division of Oil Recovery Systems Inc.)

Equipment: Enhanced Natural Degradation (END)

Remarks:

- The company offers a three-phase program: Site Assessment, Activation, and Monitoring.
- The first phase involves the determination of the extent and movement of the contamination.
- The second phase is the containment and control of the contaminant plume by depressing the water table to recover the floating contaminant. The discharged water is air stripped to remove the dissolved hydrocarbons. It is then recharged back into the aquifer with the necessary nutrients and oxygen for the degradation of the contaminants left in the soil.
- The third phase is the monitoring of the effectiveness of the treatment using groundwater samples. Adjustments of the nutrients concentration is done when required.

Composting. This technique is a form of biological degradation, but the approach is somewhat different than that previously discussed. With composting, the soil contaminated by organic materials is excavated and then aerated by mixing and/or forced aeration to enhance the growth of aerobic microbes. There are four basic types of composting systems: enclosed systems, windrows, forced aeration and land farming. All are long-term methods of treatment, taking years to biodegrade contaminants, depending upon their concentration in the soil. As in the preceding section, the micro-organisms can either be those already present in the waste organics or those introduced from other sources.

An enclosed composting system involves digesters or basins equipped with agitators or aerators. The contaminated material is simply excavated and placed into the containers and aerated. The pollutant will also drain, to some extent, from the soil and collect in the bottom of the basins. Windrowing is somewhat similar, except that the hydrocarbon soaked soil is pushed up into ridges exposing uncontaminated soil. This method creates substantial surface disturbances but needs low capital investment and has low energy requirements. Fertilizer can be added to the soil to speed up the microbial decomposition of the hydrocarbons. It is also possible to seed the windrows once the contaminant content has been reduced, and the drained surface soil from the windrows can be redistributed over the area and then seeded. These procedures will serve to dry

out the surrounding areas and encourage revegetation. Forced aeration is a variation of windrowing, in which air blowers are used to draw air from the base of the organic mass through perforated pipe. Finally, land farming involves plowing the contaminated soil into the upper layer of earth using conventional farm or construction equipment. The soil is usually reseeded and plant growth is encouraged. This technique is suitable for pollutants that decompose quickly, are not toxic to soil micro-organisms, plants or animals, and have no long-term toxic effects resulting from adsorption or ion-exchange in the soil. Also, the contaminant cannot contain substances that may adversely affect groundwater quality or soil structure, especially the soil infiltration, percolation and aeration characteristics.

Although composting has been used for many years to make soil supplements for agricultural lands, it has limited acceptance for soil treatment due to its vulnerability to weather changes, labour requirements and slow reaction. However, because it needs little capital investment and can be used in-situ, it is a viable treatment alternative for hydrocarbon-contaminated soil.

Incineration. A commonly used method of destroying organic wastes is by burning them. Soil that is saturated with hydrocarbons may be cleaned by burning the mixture in a kiln. This technique is not appropriate for large spills because there are no commercially available incinerators capable of handling large volumes of soil. However, a prototype rotary kiln has been built which is capable of processing 0.5 to 2 tonnes/h of sand containing 8 to 15 % oil. This prototype was based on a design developed by Trecan Ltd. for Environment Canada and PACE and was built and modified on the site of a spill (45,46). A similar model in stainless steel was built for the Canmar Base at Tuktoyaktuk, NWT.

Company: Trecan Ltd.
Equipment: Rotary Kiln Incinerator

Company: Canmar
Equipment: Rotary Kiln Incinerator

Fixation. This process involves the immobilization, isolation or otherwise containing of waste materials by producing a solid material from a semi-solid or liquid waste. Fixation prevents wastes from reacting with or leaching into the surrounding environment. Ideally, fixation should render the wastes nonreactive and immobile in a solid matrix that is stable, resistant to freeze/thaw cycles, has low permeability, is tolerant to high stress, and resistant to attack by biological agents. Often, the end product is used for road construction or is burned at a landfill site. The types of fixation

techniques include those that use materials such as cement, lime, thermo-plastics (e.g., bitumen, paraffin or polyethylene), and organic polymers, and techniques such as encapsulation, glassification and self-cementing. These methods are summarized and compared in Table 11 (28). All of these techniques are usually capital intensive. Stabilization using cement kiln dust, which is less expensive than cement, has been experimented with as an in-situ treatment for a sludge composed of oil-water-solids/50-35-15, the oil being a crude with heavy residual material; cement dust was used in a ratio 3:1 (dust:oil) and mixed using a bulldozer (47). An outline of some of the commercially available systems is given in Table 12 (28). The Chemfix and the Soil Recovery Inc. processes were the only mobile systems identified in these references. The Sealosafe process is not suitable for solidification of oils and solvent wastes that are not miscible with an aqueous phase.

Washing. The capacity of soil to retain oil depends somewhat on its moisture content - a soil with a higher water content will have a lower oil capacity. The technique of washing works by a mechanism involving leaching and replacement by hydraulic drive. Large amounts of water are allowed to percolate down through the oil moving the hydrocarbon downwards to a collection funnel created in the aquifer. The water and contaminant can then be recovered. This method is similar to recharge with some modifications.

One such variation is that the contaminated area can be flushed with an aqueous detergent. The detergent has a lower surface tension and it displaces oil from the pores and capillaries of the subsoil. This method should not be used without the agreement of the relevant water authorities because it may cause further contamination of the groundwater with both emulsified oil and the detergent itself.

Another method uses heated water to recharge the formation. Increasing the temperature of the product will reduce its viscosity and allow more of the hydrocarbon to be flushed into the recovery wells. The produced water from recovery wells can be reused for recharge. In order to be feasible, an economic method of application has to be determined. Although washing is a commonly used means of improving oil recovery, there has been little research or field testing of water and/or surfactant flooding in order to determine their feasibility on spills in unconfined aquifers (26).

Some examples of available equipment follow:

Oil and Hazardous Material Spill Branch, U.S. Environmental Protection Agency

Equipment: Sub-surface Soil Surfactant (28)

TABLE 11 FIXATION TECHNOLOGY (28)

Technique	Description	Advantages	Disadvantages
Cement-based	Involves the reaction of water in the waste with anhydrous portland cement. The complete process takes 28 days, but 50 to 90% of the final compressive strength is attained in seven days.	- additives available at a reasonable cost - cement mixing and handling are techniques that are well developed - easy to obtain processing equipment - cement can be added to adapt to a wide range of water contents - is tolerant of chemical variations in wastes - strength and permeability of the end-product is controlled by the amount of cement added - sealants can be added to improve impermeability of end-product	- large amounts of cement are required - the weight and volume of the end product are approx. twice that of other processes - ammonia gas is given off due to the alkalinity of the cement - low strength cement-waste mixtures are sometimes vulnerable to acidic leaching solutions - sometimes pretreatment, costlier cement types or expensive additives are needed if the wastes contain impurities affecting setting and curing of the cement
Lime-based	Aqueous solutions are mixed with lime and fine-grained siliceous materials (e.g., volcanic ash or lava deposits, fly ash) to form a concrete material. Generally, finer materials produce stronger end-products.	- additives are cheap and widely available - equipment required is easy to operate and widely available - chemistry of the reaction is well known - extensive dewatering unnecessary-water needed for curing process	- lime and additives increase volume and weight of waste - stabilized sludges are susceptible to attack by acidic solutions - setting times slower than for cement - end-product may require compaction during placement
Thermoplastic	The wastes are dried, heated and mixed with a matrix consisting of bitumen, paraffin or polyethylene. The mixture solidifies as it cools and is usually placed in containers and buried. The waste is physically (not chemically) incorporated into the polymer.	- rates of leaching lower than for cement-based methods - drying the waste reduces the volume to be treated - end-product resistant to most aqueous solutions - thermoplastic materials adhere well to incorporated materials - can recover material embedded in thermoplastic if necessary	- wet sludges must be predried - equipment is expensive and skilled labour is required - not for use with wastes which decompose at high temperatures - fire hazard associated with bitumen and strong oxidizers - objectionable oils and odours may be released during heating - if salts are allowed to rehydrate in in the matrix, they will expand and cause it to fracture - due to its plastic nature, the matrix may require a secondary container for transport and disposal
Organic Polymer	The wet or dry waste is thoroughly mixed with a monomer and an initiator is added. The solid formed, entraps particles in a spongy mass. Liquid associated with the waste must be evaporated from the polymeric mass before disposal.	- only small quantities of additives generally needed to cause mixture to set - organic resins are not as dense as cement - air curing polymers do not need high temperatures for curing	- final solidified polymer must be dried - water evaporated from curing polymer may be strongly acidic and contain high levels of pollutants - some initiators require special handling equipment (they are corrosive) - hazardous or disagreeable fumes may be released during polymerization - some polymers are biodegradable
Encapsulation	The wastes are enclosed in a coating of inert material (a jacket).	- very soluble contaminants completely isolated from the environment - no secondary container usually needed	- inert materials (resins) are expensive - large amounts of energy needed to dry, fuse and form the jacket - waste has to be dried prior to encapsulation - some resins are flammable - skilled labour is needed to accomplish the moulding and fusing operations
Glassification	Extremely dangerous wastes can be mixed with silica and fused at high temperature to form glass.	- should produce a high degree of waste containment - additives are relatively inexpensive	- energy intensive process - some components may be vapourized before combining with the molten silica to form glass - specialized equipment and trained personnel needed
Self-cementing	A small amount (8 to 10% by weight) of wastes containing large quantities of calcium sulphate or sulphite are dried and calcined to produce partially dehydrated calcium sulphate or sulphite. This material is added to the balance of the waste with other additives forming a hard, plaster-like substance.	- no major additives to be made or shipped to the processing site - should give faster setting times and and more rapid curing than similar lime-based systems - end-product is stable, inflammable and nonbiodegradable - should give effective heavy metal retention - complete drying of waste is not required - the hydration reaction uses up water	- only high sulphate and sulphite wastes can be used - similar leaching characteristics as cement and lime-based methods - energy is needed to produce the calcines cementitious material - process requires skilled labour and expensive equipment

TABLE 12 FIXATION SYSTEMS (28)

Distributor/Developer	Process
Aerojet Energy Conversion, Co. (Sacramento, CA)	Cement Organic Polymer (UF)* Bitumen
Anefco, Inc. (White Plains, NY)	Organic Polymer (UF)*
Atcor, Inc. (Peekskill, NY)	Cement
Brookhaven National Laboratory (Uptown, Long Island, NY)	Cement with organic polymers
Chemfix (Kenner, LA)	Chemfix Process (Cement)
Chem-Nuclear Systems, Inc. (Bellevue, WA)	Cement Organic Polymer (UF)*
Delaware Custom Materials (Cleveland, OH)	Cement with shale or silicates
Dow Chemical Co. (Midland, MI)	Organic Polymer (polyvinyl resins)
Dravo Lime Co. (Pittsburgh, PA)	Calcium (Cement-based)
Energy Inc. (Idaho Falls, ID)	Cement Organic Polymer (UF)*
Environmental Technology Corp. (Pittsburgh, PA)	Bentonite/Cement
General Electric Co. (San Jose, CA)	Cement
Hittman Nuclear & Development Corp. (Columbia, MD)	Cement Organic Polymer (UF)*
I.U. Conversion Systems Inc. (Horsham, PA)	Poz-O-Tech (Lime-based)
Newport News Industrial Corp. (Newport News, VA)	Bitumen
Oak Ridge National Laboratory (Oak Ridge, TN)	Cement with additives
Ontario Liquid Waste Disposal, Ltd. (Markham, Ontario)	Silicate
PEC Engineering (Paris, France)	Petrifix
Protective Packaging, Inc. (Jeffersontown, KY)	Organic Polymer (UF)*
Sludge Fixation Technology, Inc. (Orchard Park, NY)	Terra-Crete (Self-cementing)
Soil Recovery Inc. (Morristown, NJ)	Quick lime/Calcium oxide based reagent
Stabatrol Corp. (Norristown, PA)	Terra-tite
Stablex Corp. (Radnor, PA)	Sealosafe
Stablex Corp. (Ste-Therese, P.Q.)	Sealosafe
Stock Equipment Co. (Cleveland, OH)	Cement Organic Polymer (UF)*
TJK Inc. (North Hollywood, CA)	Takenaka Sludge Treatment System
Todd Research and Technical Div. (Galeston, TX)	Cement
TRW Systems Group (Redondo Beach, CA)	Encapsulation Studies for U.S. EPA
United Nuclear Industries (Richland, WA)	Cement with sodium silicate Organic polymer (UF)*
United Technologies (Sunnyvale, CA)	Organic polymer
Voest-Alpine Montagne (1015 Wein, Austria)	Lime-based
Washington State University (Pullman, WA)	Polyester encapsulation
Werner & Pfleinder Corp. (Ramsay, NJ)	Volume reduction and solidification system
Westinghouse Electric Corp. (Pittsburgh, PA)	Cement with vermiculite

*UF = Urea Formaldehyde

Remarks: - This is a concept under study only for the in-situ treatment of soils more than 0.6 m underground contaminated by slightly water soluble and hydrophobic organics or heavy metals.

- Water and surfactant are injected into the soil and the leachate is recovered through a draw-down well or interceptor trench, submersible pump or French drains (Figure 3) located down gradient from the zone of contamination. The leachate is treated above ground with chemical and/or physical treatment methods.

- Lab-scale testing has been done by:

  JRB Associates
  8400 Westpark Drive
  McLean, VA 22102

  The removals obtained for petroleum hydrocarbons were an order of magnitude better than with just water washing.

Solvent extraction. This soil treatment technique is feasible for relatively small volumes of contaminated soil that have been excavated. A solvent is mixed with the contaminated soil in a container. The operating conditions depend on the process. The contaminated solvent is processed for re-use and the clean soil is returned to the excavation site.

Oil and Hazardous Materials Branch, U.S. Environmental Protection Agency

Equipment: Solvent Extraction System (28)

Remarks: - A mobile, prototype system for use in the field to strip spilled chemicals from excavated soils and sediments.

- The system is composed of a vibrating screen classifier, water-knife/soil scrubber, soaking unit, counter-current chemical extractor, hydroclone separators/waste liquid recyclers and air cleaners.

- The soil is excavated and broken up. The contaminant is stripped from a soil slurry using water with additives. The solvent is further processed to recover the contaminant and the clean soil may be returned to the excavation site.

- Full-scale testing has been done by:

  Rexnord, Inc., Environmental Research Centre
  P.O. Box 2022
  Milwaukee, WI 53201

Sanexen International

Equipment: Extraksol

Remarks: - Skid-mounted units, each having a capacity of about two tons per hour.

- Batch system using rotating vessels to improve the soil/extraction fluid contact. Once saturated with contaminants the extraction fluid is replaced with fresh fluid and the treatment is repeated until an acceptable removal level is reached.
- The extraction fluid can be regenerated for re-use.
- Continuous system is suggested for soil quantities over 4000 tons. Delivery time for such a system should be about four months.
- Better performance is achieved when soil is a sand grain size type.

Solarchem

Equipment: Solvolox

Remarks:
- Three stages process: soil washing, solvent transfer and photooxidation.
- A hydrophilic solvent is used to extract the contaminant from the soil. The filtrate containing the organic contaminants is then concentrated in an evaporator. The contaminants from the concentrated solution are transfered to a hydrophobic solvent in a liquid-liquid extraction unit. Ultraviolet rays and ozone are used to oxidize the contaminants in the hydrophobic solvent extract.
- Decontamination cost varies with the contaminant type and concentration. Treatment cost only for a 3000 ppm PCB-contaminated soil is estimated to be 153 to 238 $U.S./$m^3$.

Gravity separation. Gravity separation is perhaps the simplest of all the soil treatment techniques. The soil is excavated and held in large bins. The hydrocarbon migrates through the soil due to the force of gravity, and is collected in catchment basins at the base of the container. There will remain the problem of removing residual amounts of the pollutant from the soil as some will be trapped in the pore spaces of the soil. (This method could easily be combined with composting to separate the balance of the hydrocarbons.) The main drawback to this technique is that the soil must be excavated making it a costly and labour intensive means of separation.

Soil venting. Volatile products such as gasoline will often remain in the ground in vapour form and migrate into building basements in the leak area. This will be most severe in dugout basements where the natural earth materials are still exposed inside the structure. The problem can be mitigated somewhat by sealing wherever possible. This is not feasible for dugout basements; therefore, a series of passive artificial vents (Figure 15) can be installed to eliminate vapours, a technique that is especially helpful during winter months when frost prevents vapours from escaping naturally through the

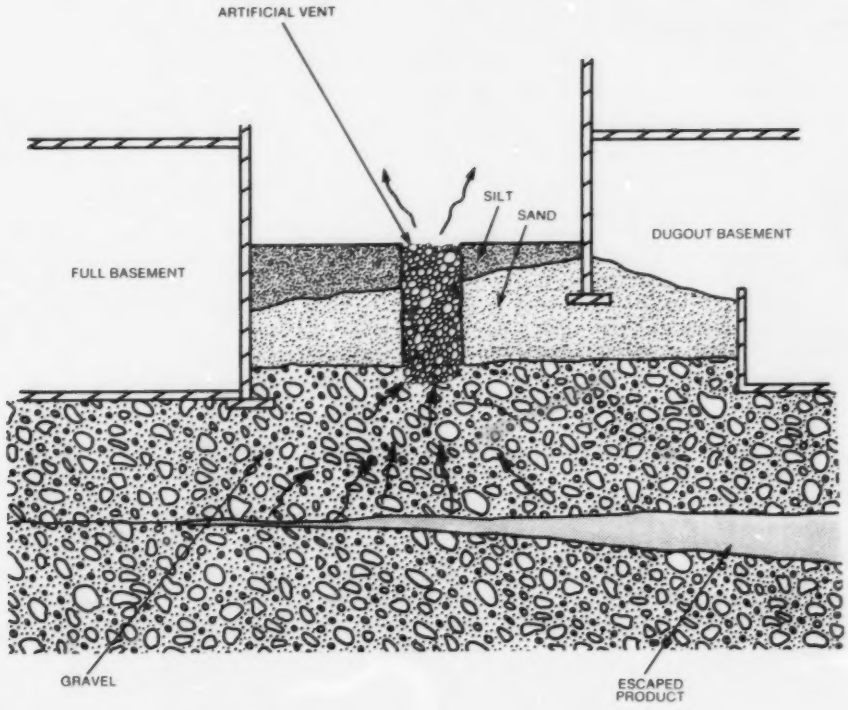

FIGURE 15 SOIL VENTING (48)

surface sediments. The assembly can also be equipped with a suction fan as necessary (21,48).

Soil venting is considered feasible in high to medium soil porosity and permeability (16). Vapour extraction systems using wells have been successful in soils having a 10^{-4} to 10^{-8} cm/s permeability range with a maximum applied vacuum of about 20-cm mercury gauge. An air-water separator may be required to protect the blower from the water in the extracted air. Short-circuiting of air from the ground surface can be reduced by covering the area to be treated. An alternative to extraction wells in situations where the contaminated soil or the depth to groundwater is less than about 4 to 5 m, is the use of perforated pipe in trench bottoms.

Dispersion in the atmosphere of the vented gases may not be acceptable and recovery of the vapours may be required. Air emissions may be controlled through the use of activated carbon adsorption or combustion. An evaporator/condenser can be used as a product recovery system before the activated carbon column. There are some drawbacks to the use of a carbon system such as fire hazards and clogging after many regenerations.

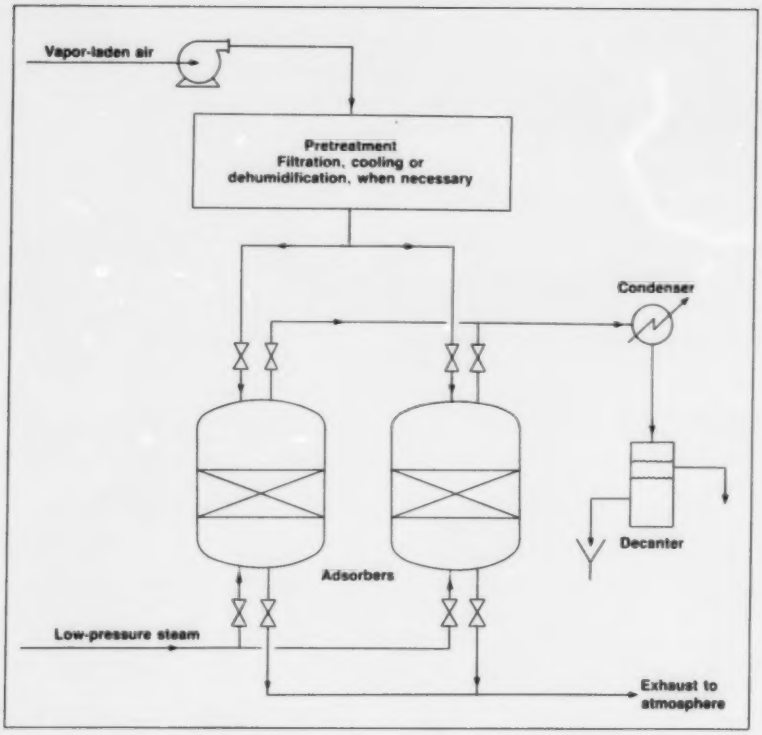

FIGURE 16 VAPOUR PHASE ADSORPTION SYSTEM (49)

A typical vapour phase adsorption system is represented in Figure 16 (49). Several portable systems are being developed in the United States (49).

In a study conducted for API in which gasoline vapours were vented from soil at a 5-year old spill site, radii of influence of 16 and 30 m from the vapour recovery wells were measured using 0.65 m^3/min and 1.1 m^3/min vacuum rates in a sandy soil. Average product recovery rates of 11 L/d and 23 L/d were observed. The effectiveness of this soil venting system was dependent on the applied vacuum intensity, the distance from the contamination source and the position between the air inlet and the vapour recovery wells (49).

A similar product recovery rate to vacuum rate ratio for a radius of influence of 12 m from the well point in sand, was observed in another gasoline spill cleanup (50).

The following is an example of available equipment:

Groundwater Technology Inc., a division of Oil Recovery Systems, Inc.

Equipment: Soil Venting System

Remarks: - It operates by drawing air through the soil causing the trapped liquid hydrocarbon to vaporize. The vapours are

pulled into subsurface vent tubes and carried through the system to a carbon adsorption system or to the atmosphere where they are dispersed.

- It is for use after the bulk amount of the spill has been cleaned up and will eliminate residual vapour problems - it is used to remove hydrocarbons that have saturated the soil and cannot be displaced with water.
- Able to remove between 12 to 18 L/h of liquid gasoline if 0.1 % gasoline vapour/air mixture is being drawn through the system.
- Available as a secondary recovery system with the Scavenger system, as an interceptor vent or as a basement vent.

Steam stripping. Vacuum-assisted in-situ steam stripping of contaminated soil is being studied by the U.S. EPA. The project will include a small-scale feasibility study for a range of chemicals and soils followed by the development of a small pilot stream stripping unit using vacuum to improve the steam recovery. Design of a field unit will then be performed. Lab-scale testing is being performed by A.E. Lord, R.M. Koerner and V. Murphy, Drexel University, Philadelphia, Pennsylvania.

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APPENDIX

PARTIAL LISTING OF DISTRIBUTORS/SUPPLIERS, COMPANIES AND AGENCIES CONSULTED

APPENDIX PARTIAL LISTING OF DISTRIBUTORS/SUPPLIERS, COMPANIES AND AGENCIES CONSULTED

Company	Product
AFL/INDUSTRIES INC. 1149 Howard Drive West Chicago, IL 60185 (312) 231-7555 (800) 323-1732	AFL/Clark Oil Stop Valve
ANCO CHEMICALS LTD. - P.O. Box 400 Maple, Ontario L0J 1E0 (416) 832-2276 - 6905 Hebert Street Ville Ste-Catherine, Québec J0L 1E0 (514) 632-0950	Imbiber Beads
BAT ENVITECH INC. P.O. Box 7826 3777 Long Beach Blvd. Long Beach, CA 90807 (213) 427-6824	BAT Groundwater Monitoring System
B.C. RESEARCH 3650 Wesbrook Mall Vancouver, B.C. V6S 2L2 (604) 224-4331	Tank Leak Detector
CAE (Canadian Aviation Electronics) P.O. Box 548 Belleville, Ontario K8N 5B2 (613) 966-8086	FRP Tank Manufacturer
CALGON CANADA 27 Finley Road Bramalea, Ontario L6T 1B2 (416) 457-5310	- Interphase System - Gravity Flow Carbon Adsorption
CANMAR P.O. Box 200 Calgary, Alberta T2P 2H8 (403) 231-8008	Rotary Kiln Incinerator
CONTEL ENGINEERING LTD. 40 Torlake Crescent Toronto, Ontario M8Z 1B3 (416) 252-4148	Consultant Re-membrane Liners

Company	Product
CORROSION SERVICES COMPANY LTD Toronto, Ontario (416) 630-2600	
CLAWSON TANK COMPANY 4701 White Lake Road Clarkson, MI 48016 (313) 625-8700	Double-walled Tanks
CLEAN ENVIRONMENT ENGINEERS 38 Caselli Avenue San Francisco, CA 94114 (415) 521-2161 (415) 621-2722	SOS Skimming System
CROWLEY ENVIRONMENTAL SERVICES CORP. 3400 E. Marginal Way S. Seattle, WA 98134 (206) 682-4674 (206) 682-4898	Response Equipment Distributor
D.J. PETROLEUM MAINTENANCE Box 902 Falher, AB Mov. XJB 2449 (403) 837-2468	Tank Installation and Testing, Response To Leaking Tanks
DETOX INC. 8721 Woodglen Point Dayton, OH 45459 (513) 433-7394	Detox Portable Industrial Treatment Systems
EMCO INC. 1015 Louisiana Street Little Rock, AR 72207 (501) 374-7878	
EMTEK INC. Northwood Executive Park 10 Northern Blvd. Amherst, NH 03031 (603) 883-7111	Groundwater Pollution Control
ENVIRONMENT CANADA Environmental Emergencies Technology Division River Road Laboratories Ottawa, Ontario K1A 0H3 (613) 998-9622	Mobile RO/UF Unit

Company	Product
ETHYL CORPORATION Houston, TX (609) 452-8600	Ethyl Tank Sentry (Tank Leak Detector)
FLEXALON P.O. Box 8697 The Woodlands Houston, TX (713) 292-3233	Membrane Installer
FMC CORPORATION, SPECIALTY CHEMICALS DIVISION 2000 Market Street Philadelphia, PA 19103 (215) 299-6763	Aquifer Remediation Systems Enhanced Bioreclamation Program
GENELCO INC. 11649 Chairman Drive Dallas, TX 75243 (214) 341-8410	Soil Sentry Gas Leak Detector
GEOLOGICAL SURVEY OF CANADA 601 Booth Street Ottawa, Ontario K1A 0E8 (615) 995-5745	
GEONICS LIMITED 1745 Meyerside Drive Unit B Mississauga, Ontario L5T 1C5 (416) 676-9580	Terrain Conductivity Measurements

Canadian Owners of Heath Petro-tite Leak Detector

HEATH CONSULTANTS LTD. 954 Leathorne Street London, Ontario N5Z 3M5 (519) 686-6446 Mr. D. Brochu	Heath Petro-tite (Leak Detector)
IRVING OIL LTD. P.O. 1421 St. John, N.B. E2L 4K1 (506) 632-2000	Leak Detector

Company	Product
CREEDES PETROLEUM EQUIPMENT & MAINTENANCE LTD. 23 Norwood Road Charlottetown, PEI C1A 6P7 (902) 892-6036 Mr. K. Smith	Leak Detector
GENCO 19 Akerley Dartmouth, N.S. B3B 1J6 (902) 469-5325	Leak Detector
Research & Productivity Council P.O. 6000 College Hill Road Fredericton, N.B. E3B 5H1 (506) 452-8994	Leak Detector
WATER MANAGEMENT SERVICES LTD. P.O. 1116 776 McLeod Avenue Fredericton, N.B. E3B 5C2 (506) 458-8288	Leak Detector
ESSO CANADA LTD. 1981 McGill College Montreal, P.Q. H3A 3B2 (514) 287-7452 Mr. D. Robinson	Leak Detector
GROUNDWATER TECHNOLOGY INC., a division of OIL RECOVERY SYSTEMS, INC. 8435 Notre Dame East, Suite 2 Montreal, P.Q. H1L 3L3 (514) 353-6939	Leak Detector
SHELL CANADA LTD. 758 Sherbrooke St. W. Montréal, P.Q. H3A 1G1 (414) 287-7213 Mr. R. Desmarais	Leak Detector
SANEXEN INTERNATIONAL INCORPORATED 3027 Harvester Road Burlington, Ontario L7N 3G7 (416) 681-3366	Leak Detector

Company	Product
ESSO CANADA LTD. 10060 Jasper Avenue Edmonton, Alberta T5J 3R8 (403) 420-8490 Mr. M. Chapman	Leak Detector
B.C. PETROLEUM ASSOCIATION Suite 1004, Kapilano 100 100 Park Royal West Vancouver, B.C. V7T 1A2 (604) 926-7431 Mr. Green	Leak Detector
Canadian Owner of Horner EZY-CHEK Leak Detector	
HORNER CREATIVE METALS INC. 211 East Grove Kawkawlin, Michigan 48631 (517) 684-7180 Mr. P. Schuster	Horner EZY-CHEK Tank Leak Detector
E-JAY PETROLEUM SERVICES 242, 62nd Avenue, S.E. Calgary, Alberta T2H 2E6 (403) 252-4409	Leak Detector 1984
WESTERN OIL SERVICES LTD 8264 Ontario Street Vancouver, B.C. V5X 3E4 (604) 321-1266 Mr. R.F. Bartlett	Leak Detector
RUDIES PETROLEUM No. 5, 3015 Sixsmith Road Kelowna, B.C. V1V 1L2 (604) 765-1418 Mr. N. McWilliam	Leak Detector
Canadian Owner of Hunter Leak Detector	
HUNTER ENVIRONMENTAL SERVICE 18 Great Valley Parkway Suite 406 Nalborn, PA 19355 (315) 296-7380	Tank Leak Detector

Company	Product
GROUNDWATER TECHNOLOGY INC., a division of OIL RECOVERY SYSTEMS INC. 8435 Notre Dame East, Suite 2 Montreal, P.Q. H1L 3L3 (514) 353-6939	Leak Detector
K-V ASSOCIATES, INC. 281 Main Street, P.O. Box 574 Falmouth, MA 02540 (617) 540-0561	Groundwater Flowmeter
MARTEK INSTRUMENTS INC. 17302 Daimler Street P.O. Box 16487 Irvine, CA 92713 (714) 540-4435	Groundwater Monitor
MARCLIN INDUSTRIES Nisku, Alberta (403) 955-2514	Tank Manufacturer
MEMCARE CORP. 1435 Prince of Wales Drive Suite 1008 Ottawa, Ontario K2C 1N5 (613) 723-1981	Reverse Osmosis Systems
MOONEY EQUIPMENT CO. INC. 7780 Townsend Place New Orleans, LA 70126 (504) 241-0453	Tank Leak Detector
NEPCCO, EQUIPMENT DIVISION 29 Wall Street Foxboro, MA 02035 (617) 543-8458	- Petropurge/Hydropurge - AS and CA Treatment Systems - Whole Range of Detectors, Monitors
OIL AND HAZARDOUS MATERIAL SPILL BRANCH, U.S. ENVIRONMENTAL PROTECTION AGENCY Municipal Environmental Research Laboratory Woodbridge Avenue Edison, NJ 08837 (201) 321-6634	- Carbon Adsorption System - Solvent Extraction System - Sub-surface Soil Surfactant System

Company	Product
OIL RECOVERY SYSTEMS INC. - GROUNDWATER TECHNOLOGY INC. - 1420 Providence Hwy, Suite 128 Norwood, MA 02062 (617) 769-7600 - 8435 Notre Dame Street, East Suite 2 Montreal, Quebec H1L 3L3 (514) 353-6939	- Scavenger System - AS, CA, Soil Venting and Biodegradation Treatment Systems - Whole Range of Detectors, Monitors
OPW-DOVER CORPORATION 5460 Royalmount Avenue, Suite 100 Mount Royal, Quebec H4P 1H7 (514) 731-9481	Optic Liquid Level Sensor
PACE (Petroleum Association for Conservation of the Canadian Environment) 1202-275 Slater Street Ottawa, Ontario K1P 5H9 (613) 236-9122	
POLYBAC CORP. 8455 Wilddeer Trail P.O. Box 30 Roscoe, IL 61073	Polybac Mutant - Baterial Hydrocarbon - Degrader
P.R. MALLORY & CO., INC. 4760 Kentucky Avenue Indianapolis, IN 46241 (317) 856-3857	Pollulert Detector
REXNORD INC. Environmental Research Centre P.O. Box 2022 Milwaukee, WI 53201	Solvent Extraction System
RMT INC. 1406 E. Washington Avenue Suite 124 Madison, WI 53702 (608) 255-2134	Underground Leak Detection
RNG EQUIPMENT 32 Stouffville Drive Toronto, Ontario M9W 1A8 (416) 249-7383	NEPCCO Products Distributor

Company	Product
ROMICON INC. - a subsidiary of ROHM & HASS CO. 100 Cummings Park Woburn, MA 01801 (617) 935-7840	Hollow Fiber UF System
SANIVAN INC., a division of SANEXEN INTERNATIONAL INC. 1705, $\frac{e}{}$ Avenue Pointe aux Trembles Montreal, Quebec H1B 5M9 (514) 353-9170	NEPCCO Product Distributor
SANEXEN INTERNATIONAL INC. 7777 Louis-H-Lafontaine Blvd Anjou, P.Q. H1K 4E4 (514) 355-3351	Soil Treatment System
SEAGOLD INDUSTRIES CORP. 4008 Myrtle Street Burnaby, B.C. V5C 4G2 (604) 437-4445	Reverse Osmosis Systems
SEPROTECH SYSTEMS INC. 2378 Hollylane Ottawa, Ontario K1V 7P1 (613) 523-1641	Reverse Osmosis Systems
SHELL CANADA LTD. Toronto, Ontario (416) 443-7032 Mr. J. Witherspoon	PACE Leak Detector
SMITH & DENISON 1581 Industrial Parkway West Suite No. 3 Hayward, CA 94544 (415) 782-9788	Tank Leak Detector
SOIL RECOVERY INC. P.O. Box 2147 95 Madison Avenue Morristown, N.J. USA 07960 (201) 540-0566	Soil Encapsulation

Company	Product
SOLARCHEM 516 Gordon Baker Rd Willowdale, Ontario M2H 3B4 (416) 495-9905	Soil Treatment Process
SPEARHEAD TECHNOLOGY INC. Ste 704-525 Seymour Street Vancouver, B.C. V6B 3H7	STI 2X12 and 2X4 Monitors (Underground Tank Monitor)
SRI INTERNATIONAL Menlo Park, CA (415) 424-1251	Tank Leak Detector
TELEDYNE GEOTECH Box 469007 Garland, TX 75046 (214) 271-2561	Leak Monitor
TOTAL CONTAINMENT 215 Colonnade Road Nepean, Ontario (613) 226-4873	- Total Container - Degradable Cable Leak Detector
TRECAN LIMITED 4530 Dixie Road Mississauga, Ontario L4W 1N2 (416) 625-4030	Rotary Kiln
VACUTECT 16900, 107 Avenue P.O. Box 2404 Toronto, Ontario T5J 2S1 (403) 483-3506 M.E. Adams	Tank Leak Detector
VEEDER-ROOT CO. 70 Sargent Street Hartford, CT 06102	TLS 250 Underground Leak Detector
WARREN ROGERS ASSOCIATES INC. 65 Bellevue Avenue Newport, RI 02840	Corrosion Model
ZENON ENVIRONMENTAL INC. 845 Harrington Court Burlington, Ontario L7N 3P3 (416) 639-6320	Reverse Osmosis Systems